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EVAPORATION FROM THE SURFACES OF WATER AND RIVER-BED MATERIALS

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INTRODUCTION

The Irrigation Field Laboratory at Denver, Colo., where the following experiments were made, was established for the purpose of studying from an engineering standpoint problems connected with the utilization of water in irrigation. It is a laboratory of such size and kind that natural phenomena may be observed under conditions somewhat less artificial than are usual in laboratory work. An examination of figure 1 will show the general exposure and topography of the laboratory tract. This field (22),[1] though it has the conveniences and facilities of a city location, is as open to the elements as the prairie homestead.

A maximum elevation of 5,346.4 feet above sea level is reached at one point of the tract. The surrounding country, except to the east, is lower. The grade to the east is very slight and the country is open prairie. All buildings in the immediate section of Denver are shown; these are generally of the one-story or bungalow type, and offer no interference with experiments that may be in progress, since the nearest is some 200 feet from the laboratory. Figure 2, which shows the layout of the laboratory for the season of 1916, indicates the location of such facilities as electric power, water supply, etc. The hillside provides a 20 per cent slope for the flow of water and furrow work. The panorama (Pl. 33) supplements the information given by figures 1 and 2. Surrounded by a 6-foot 3-inch mesh woven wire fence, with top and bottom barbed wires, the field has been free from animals. A rule that has been rigidly enforced is that visitors are not permitted except when accompanied by some member of the organization.

At the beginning plans were started for a study of duty of water and movement of water through soils. Evaporation has a large part in the apparent efficiency of the use of irrigation water. Evaporation measurements and data available were not considered sufficient for the requirements of the proposed work. It was therefore necessary at first to carry

Reference is made by number to "Literature cited," p. 259–261.

on quite an extensive evaporation investigation. Available funds limited the work of 1916 to this evaporation study, divided into two important parts—that from water surfaces and that from the surfaces of riverbed materials.

PART I.—EVAPORATION FROM WATER SURFACES

An early study of evaporation was that of Perrault, who worked with water and soils in 1670 (20). Dalton in 1802 (6) first put his investigations into definite form, and Dalton's law has been used by more recent experimenters as a basis for the expressions which they have proposed for calculating evaporation rates. A bibliography of some length prepared in 1908 (19) would tend to show that evaporation research is not in a pioneer state. Noteworthy among the investigations are these: Thirteen years' work at Lee Bridge, London, England (12); 11 years' records at Boston, Mass. (9); records at Rochester, N. Y., from 1891 to the present (21); records at Fort Collins, Colo., from 1887 to the present (5, 25); several investigations of the Army engineers (15); measurements made at Salton Sea (2); at Owens Valley (18); Coyote (7); and Kingsburg, Cal. (4); and miscellaneous studies by the United States Weather Bureau, the United States Reclamation Service, the United States Geological Survey, and the Division of Irrigation Investigations of this Office. However, a recent paper (8) describing the problem of arriving at the amount of evaporation from a reservoir brought out such discussion as to indicate that there is much uncertainty concerning the interpretation of the available data. Regarding the rates of evaporation from water surfaces of varying sizes, one investigator (3, p. 1134) says regarding the coefficients proposed:

> These should be further verified if possible.

Other important points were not definitely determined, and fundamental engineering data upon which to base irrigation research were not available. Accordingly arrangements were made to make studies along the following lines:

(*a*) Variation in the amount of evaporation from pans of varying sizes.

(*b*) Variation in the amount of evaporation from pans of varying depths.

(*c*) A comparison of the amount of evaporation from flowing and still water.

(*d*) A comparison of the results obtained from different types of so-called standard evaporation pans.

(*e*) A comparison of the evaporation amounts from round pans and square pans of small size.

(*f*) An extension of the results of experimental pans to larger water surfaces.

The results of these studies are presented, not as formulas which may be misinterpreted and used where there is no justification for their use, but as curves based upon the original data which clearly show the limits

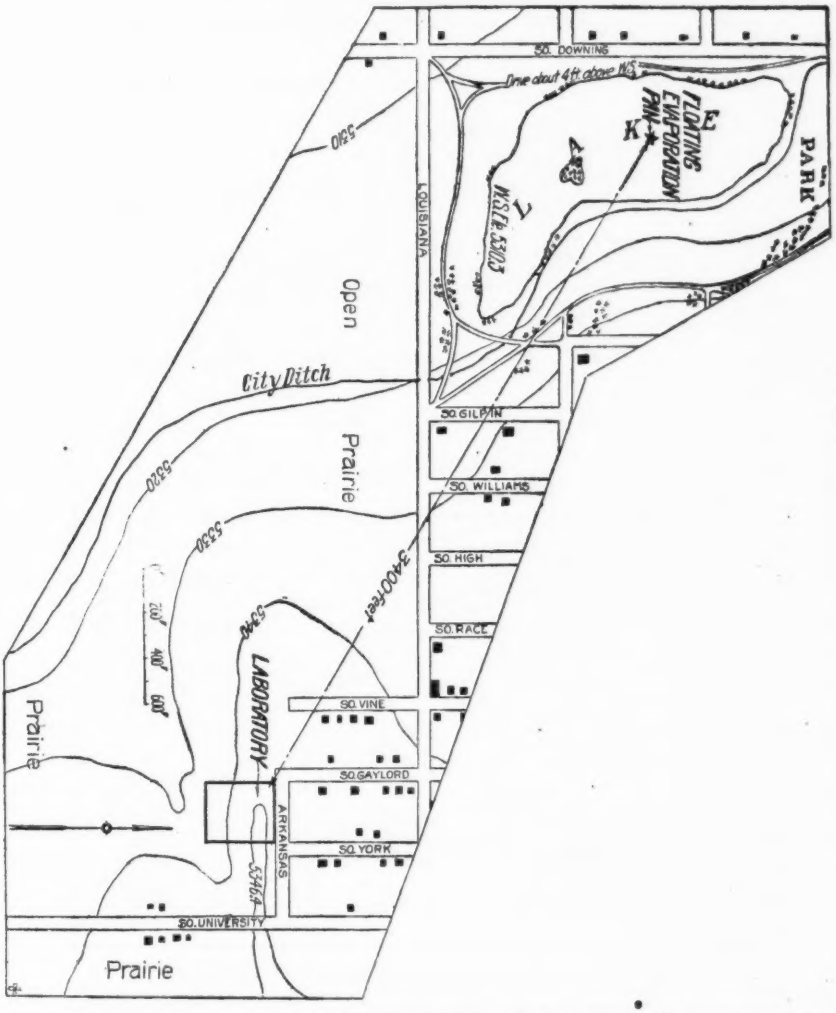

FIG. 1.—Map showing the general exposure and topography of the section of South Denver, Colo., adjacent to the Irrigation Field Laboratory of the Office of Public Roads and Rural Engineering.

of application of these data, or as coefficients from these curves. It is the aim to make this investigation of practical value to the hydraulic engineer, in direct contradiction to the statement below, which shows the

attitude which has characterized some of the past evaporation investigations.

Of course, hydraulic and irrigation engineers need to know the loss of water by evaporation, but in nature this is so mixed up with seepage, leakage, and consumption by animals and plants that our meteorological data are of comparatively little importance. (1, p. 255.)

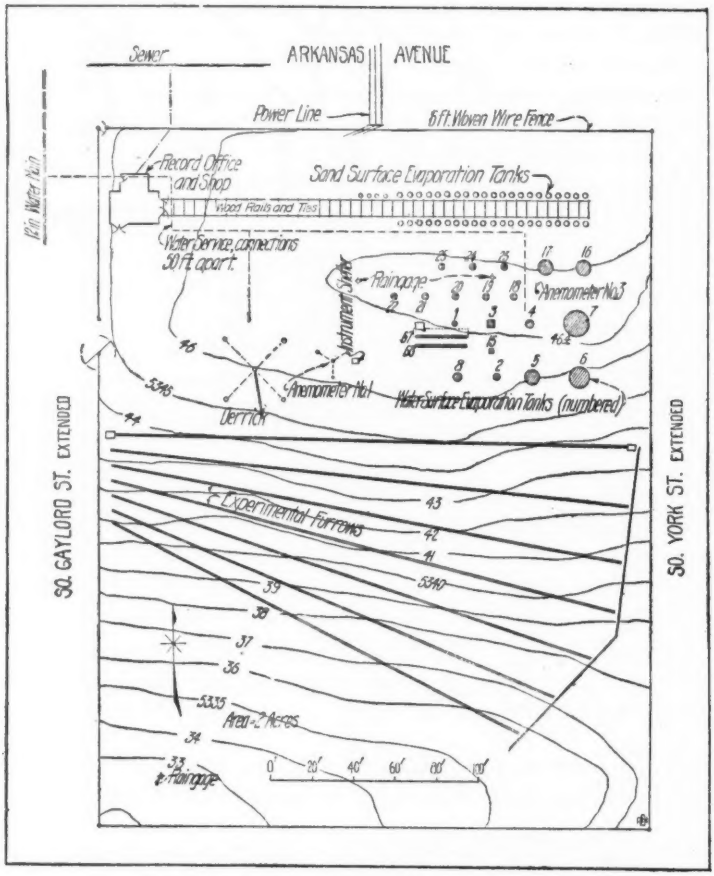

FIG. 1.—Map showing layout of Irrigation Field Laboratory for season of 1916.

EQUIPMENT

The apparatus necessary for the work, including all evaporation pans, all measuring devices for evaporation, and all meteorological instruments, were specially installed for the investigation. All evaporation pans and tanks were numbered in the order of their installation. Since the numbering also groups tanks of similar style, it has been followed throughout

this discussion. The number is given, together with the description, in Table I. All tanks are galvanized metal. The location of each is shown in figure 2.

TABLE I.—*Description of pans used in evaporation studies*

Tank No.	Exposed area.	Depth.	Water depth.	Set in ground.	Remarks.
		Feet.	*Feet.*	*Feet.*	
1	1 foot diameter	3	2.75	2.75	Similar to figure 3, *B*.
2	2 feet diameter	3	2.75	2.75	Do.
3	3 feet square	3	2.75	2.75	Similar to figure 3, *B;* shown in Plates 34, *B*, and 36, *B*.
4	3.39 feet diameter	3	2.75	2.75	Similar to figure 3, *B;* shown in Plate 34, *C*. Hoff evaporimeter is attached to this tank.
5	6 feet diameter	3	2.75	2.75	Similar to figure 3, *B*.
6	9 feet diameter	3	2.75	2.75	Do.
7	12 feet diameter	3	2.75	2.75	Similar to figure 3, *B*, and shown in Plates 34, *C*, and 35, *B*.
8	4 feet diameter	.83	.62	Above.	Similar to figure 3, *A*. United States Weather Bureau standard for class A station. Shown in Plate 37, *A*.
9	3 feet square	1.5	1.25	.....	Similar to figure 3, *C*. United States Geological Survey standard floating pan. See Plate 37, *B*.
14	.....	.....	.....	.....	Piche evaporimeter in instrument shelter.
15	1.77 feet square	3	2.75	2.75	Similar to figure 3, *B;* shown in Plate 36, *B*.
16	6 feet diameter	2	1.75	1.75	Similar to figure 3, *B*.
17	do	1	.75	.75	Do.
18	2 feet diameter	6	5.75	5.75	Do.
19	do	2	1.75	1.75	Do.
20	do	1.5	1.25	1.25	Do.
21	do	1	.75	.75	Do.
22	do	.50	.25	.25	Do.
23	do	1	.75	.75	Similar to figure 3, *B;* shown in Plate 36, *B*. Heated by electric lamp.
24	do	1	.75	.75	Do.
25	do	1	.75	.75	Do.
26	1.77 feet square	3	2.75	2.75	Similar to figure 3, *B*, but arranged for water circulation.
67	1 by 25 feet	.50	.25	.25	Shown in Plate 36, *A*. Arranged for flowing water.
68	.....	.....	.....	.....	Similar to tank 67, but water does not flow.

Throughout the work actual measurements of evaporation were made by hook gage, observations being to the water surface with the hook gauge set at the definite and fixed datum on the rim of the tank. The type of gage used is that developed by E. J. Hoff, of this Office, for evaporation work (24) and is shown in Plate 34, *A*. But two gages were used throughout the progress of all the measurements, one of them kept for use with tank 9 (floating) and the other for use at the labora-

tory proper. A Hoff recording gage (16) was installed in connection with tank 4, making it possible to keep a continuous record of the lowering of the water surface of that tank. The Weather Bureau type of

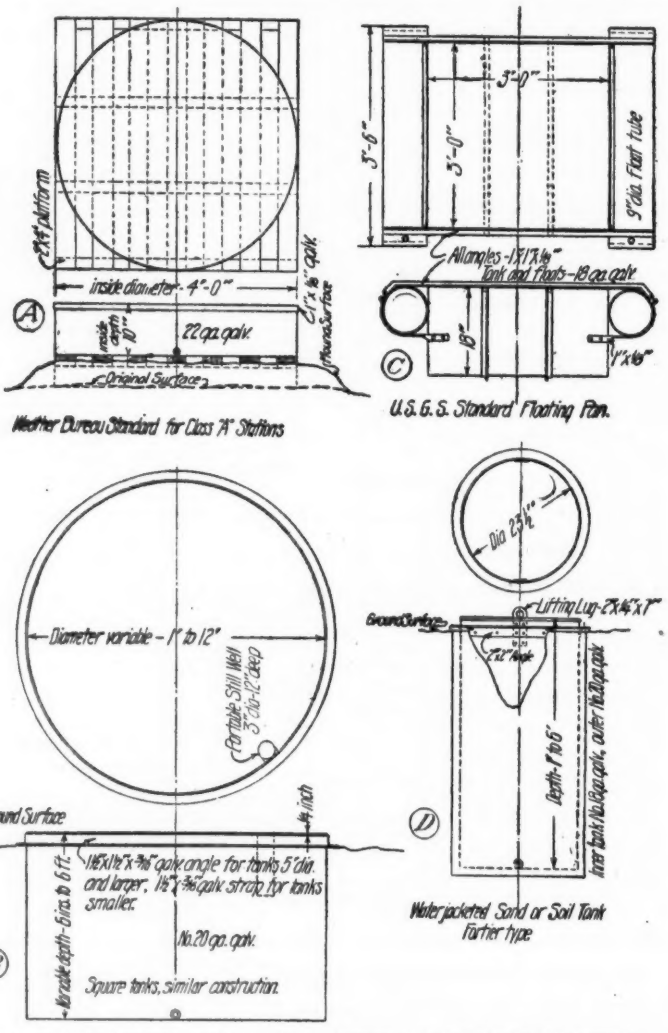
3"x5" platform
Inside diameter - 4'-0"
Inside depth 10"
22 ga. galv.
Ground Surface
Original Surface
Weather Bureau Standard for Class "A" Stations
3'-0"
3'-6"
3'-0"
9" Dia. Float tube
All angles - 1"x1"x1/8"
Tank and floats - 18 ga. galv.
18"
1"x1/8"
U.S.G.S. Standard Floating Pan.
Diameter variable - 1" to 12"
Portable Still Well
3'-0"-12" deep
Ground Surface
1/4 inch
1 1/8"x1 1/2"x 3/16" galv. angle for tanks 5' dia. and larger. 1 1/2"x 3/16" galv. strap for tanks smaller.
No. 20 ga. galv.
Variable depth - 6 ins. to 6 ft.
Square tanks, similar construction.
Dia 2.5 1/2"
Lifting Lug - 2"x4"x1"
Ground Surface
2"x2" Angle
Depth - 1' to 6'
Inner tank No. 18 ga. galv., outer No. 20 ga. galv.
Water jacketed Sand or Soil Tank
Fortier type

FIG. 3.—Sketch showing types of evaporation tanks in use at the Irrigation Field Laboratory.

still well (17) was used in tank 8, but with the Hoff gage. During the early spring months a special portable still well (fig. 3, *B*) was used when observations were taken at the other tanks. Later in the season

its use was discontinued, wind conditions being such that it was no longer necessary.

Instruments were installed for making quite complete meteorological records to accompany the evaporation figures. All apparatus were of the standard type in use by the Weather Bureau and were accurately calibrated. The location of the instrument shelter is shown in figure 2 and Plate 33. In addition to the maximum and minimum thermometer equipment, it housed the Piche evaporimeter, thermograph, and hygrograph. Both sling and whirling psychrometers were used. Three anemometers were in use, two being shown in figure 2—No. 1 on a 14-foot tower and No. 3 with cups about 2 feet above the ground to conform with Weather Bureau specifications for class A evaporation stations. The anemometer register attached to No. 3 is in the record office. No. 2 was located on the Washington Park Lake near by. The cups of this instrument were about 2 feet above the water (Pl. 37, *B*). A test run of the three instruments is shown in Plate 35, *A*. Four rain gages were in use during the season—three at the laboratory, as shown on the sketch, and one at the lake.

Water temperature records were obtained by the use of maximum and minimum thermometers with the bulb immersed to the depth 0.05 foot in the tanks. The arrangement shown in tank 3 (Pl. 34, *B*) was first used. Later, the thermometers were floated in the water, held up by means of a test tube 1 by 8 inches. This means allowed a control of the depth of the bulb without adjustment after the installation and further placed all metal under the surface. Careful comparisons showed that the effect of this glass tube is not measurable, either in amount of evaporation by a hook gage reading to 0.001 foot or in water temperature by thermometers reading to 1°, on a tank 2 feet in diameter. The thermometer tube without the metal mounting was tried, but the breakage in wind made a continuance inadvisable. Floating maximum and minimum thermometers in tank 8 are shown in Plate 37, *A*. A thermograph for water was attached to record continuously the temperature of the water at the surface of No. 4.

The barometer and barograph were located in the record office.

OBSERVATIONS

Tanks 1 to 8 were installed and were ready for use on November 1, 1915. Observations were begun at that time, records of evaporation being kept, and full readings from all meteorological instruments were taken. Other tanks were added from time to time until the end of the season 1916. The dates of the increase of equipment are indicated by the dates in the various tables presenting detailed results of the work.

Throughout care has been taken to make all observations in accordance with the rules of the United States Weather Bureau; and, in case

there are differences in methods, that recommended for evaporation (17) work has been followed. For example, the Denver branch of the Weather Bureau makes observations regularly at 6 o'clock mountain time. Weather Bureau regulations for evaporation observations recommend 7 o'clock, which hour has been used as far as possible, both morning and night. Readings were taken once a day from the beginning of the work until April 1, 1916. From then until October 5, 1916, observations were made twice a day, and then for the remaining portion of the year discussed herein regular readings at 7 a. m. only. Special and check readings were taken at various times of the day and night.

ACCURACY OF MEASUREMENTS

No observer worked for a shorter time than one month, during which period he was responsible for all the readings from a particular set of instruments or tanks. He made from 60 to several hundred observations. Thus, the error resulting from frequent change of men, that of personal equation, has been eliminated as far as possible.

The hook gage used for determining water losses by evaporation is calibrated to 0.001 foot. Neither the gage used at the lake nor the one at the laboratory was changed throughout the season. The datum on each tank remained unchanged also. Some difficulty was expected and found when measurements were made during winds. The still well was of great benefit on the smaller pans, but on the large tanks a high-velocity wind piles the water up at one side, so that a hook-gage reading might not necessarily indicate the true water level for the pan as a whole. Check observations were always made after a windstorm, and, even though individual figures were in error, the weekly totals, which have been used in the computations, have eliminated largely the errors due to wind movement. Plate 34, *B*, shows another result of a windstorm. The blown sand is caked at the side of the tank. The amount that actually is blown into the tank is difficult to estimate, but is small for the year. The catching of sand can not be prevented when the tank is exposed where sandstorms occur. Attention is called to Plate 34, *C*, which shows a typical winter condition. Regular observations of evaporation were not attempted for the time during which the ice surface was not readily broken. This period is indicated on the table of results. The figures are more consistent than was expected, since the addition by snow to an evaporation tank, having the surface of the water at about the same level as the ground surface at that point, can not be accurately determined from rain-gage results. Water in the tank may be slightly warmer than freezing at the beginning of the snowstorm, and all the snow may be retained by the tank. It then becomes colder and freezes; part of the snow may then drift up against the rim of the tank and part be

blown away, or, without wind, it may cover the ice evenly. The larger tank shown in Plate 34, *C*, has but little snow on the ice; the smaller has considerable, frozen around the rim. Measurements from tanks of this type where the water is frozen for a part of the year, while of some value, do not necessarily show the true evaporation.

Anemometer readings were taken to 0.1 mile, and in the test shown in Plate 35, *A*, the two anemometers at the ends checked within 0.2 mile for 24 hours. A correction scale for the instrument in the center was prepared from a two weeks' run, and an accuracy of about 0.4 mile in 24 hours was obtained in comparison with the two others.

All thermometers used are calibrated to 1 degree; readings were taken to the nearest half-degree. Each of the thermometers in use had been compared with a standard thermometer, and in no case has a difference in scale readings of more than 0.25° been found. Only the highest grade instruments of recognized standard makes have been purchased.

DETAIL WORK OF OBSERVATIONS

The forms made up for work at the Denver laboratory show the readings taken at each regular observation. In addition to these, there were many additional records and check readings made.

Two special forms are used. The first has the following columns: "Date;" "Time;" general heading "Barometer," under which come "Attached thermometer," "Observed barometer," "Correction," "Corrected barometer;" general heading "Thermometer," under which are "Set maximum," "Minimum," "Maximum," "Wet," "Dry," "Dew point," "Relative humidity;" the general heading "Precipitation," covering "Beginning," "Ending," "Rain gage No. 1 (inches)," "Rain gage No. 2 (inches)," "Snowfall (inches);" and the heading "Wind," which is subdivided into "Direction at time," "Anemometer No. 1, movement since last reading," "Anemometer No. 2, movement since last reading," "Hours since last reading;" and several columns for remarks or additional readings. The second form is used for evaporation alone and has the columns headed: "Date;" "Time;" "Hours since last observation;" general heading "Evaporation Tank No.," which covers the observations on that particular tank; "Hook gage, evaporated since last observation," a blank column for filling notes, maximum thermometer, minimum thermometer. Space for five evaporation tanks and remarks is available on one form.

New record sheets are required each week on the thermograph for air, thermograph for water, hydrograph and barograph. These changes are made Monday forenoon. Twenty-four hours are covered by each sheet of the anemometer register, and the requirement of new sheets for the evaporimeter depends upon the rate of evaporation.

EVAPORATION FROM CIRCULAR LAND TANKS OF DIFFERENT DIAMETERS.

This study, the first one begun at the laboratory, was started in November, 1915, and the results of one year's work are given. Tanks 1, 2, 4 (Pl. 34, *C*), 5, 6, and 7 (Pl. 34; *C*, 35 *B*), described previously, are of a type used by the Office of Public Roads and Rural Engineering and at several State Experiment Stations throughout the country. This general style of tank most nearly approximates the reservoir, and the results obtained can be more safely extended to the reservoir of some size. While of metal, but a small rim of this metal is above the ground surface; hence, but little heat derived from the sun's rays is conducted to the water. Further, since the tank is largely below the ground surface, radiation from the tank takes place from the water surface only. The same conditions are true of the reservoir. The more "unnatural" evaporation pan, that setting wholly above the ground and usually made of metal, is subjected in the greatest possible extent to the concentration and radiation effects of the metal. It has long been known that temperature has some effect upon the rate of evaporation. It seems quite evident that results obtained from tanks of the type where the water is below the ground surface, especially those of large size, can be more safely extended to the reservoir than results from the tanks with all sides exposed to the air.

The detailed figures of the year's results from this set of tanks are shown in Table II. Figure 4 shows the relation graphically. In the table (also the curve) the evaporation from the largest tank, No. 7, which is 12 feet in diameter, is taken at 100 per cent as a basis for further computation. The actual depths are given in inches as well as percentages. The period from March 6 to November 13, 1916, was such that very little ice interfered with measurements, and the figures shown are evaporation from a free and an open water surface. The percentages for this period run very near to those for the entire year. Over the range of areas 0.785 square foot to 113.1 square feet, or diameters 1 foot to 12 feet, the range in evaporation for the year is 76.18 to 49.16 inches, and in percentage 154.9 to 100 per cent.

At all times when a water surface is free from ice capillarity is pulling the water up on the metal of the tank at all points of the circumference, and wave action also wets the side of the tank, thus adding to the area from which evaporation takes place. These forces may or may not supply the water as fast as it can be evaporated from this wet surface. For the smallest tank this wet strip of metal is 3.14 feet long, or the ratio of this length to the exposed area of the tank is 3.14 to 0.785 = 4.0. This same ratio for the tank 12 feet in diameter is 37.70 to 113.1 = 0.333. Thus, if the wet strips are of the same width, the effect is 12 times as great for the small tank as for the large one. However, wave action will tend to wet a wider strip on the large tank and tend to equalize the effect on the two tanks.

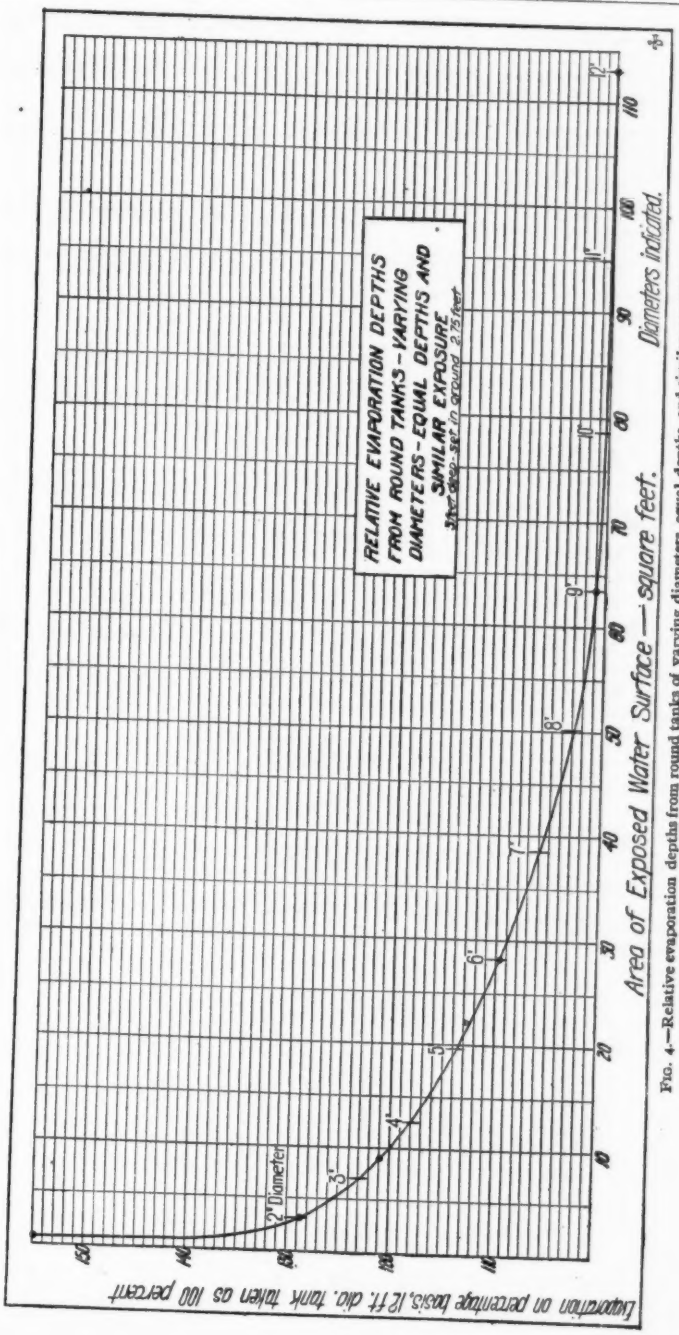

FIG. 4.—Relative evaporation depths from round tanks of varying diameters, equal depths, and similar exposure.

TABLE IV.—*Relation of amount of evaporation to size of exposed area of circular evaporation tanks set in the ground*

Week ending—	Tank 7.		Tank 6.			Tank 5.			Tank 4.			Tank 2.			Tank 1.			Mean air temperature (Maximum + minimum ÷ 2).	Mean relative humidity from hydrograph records.	Total wind movement.
	Evaporation depth.	Mean water temperature.	Evaporation depth.	Evaporation (tank 7, 100 per cent).	Mean water temperature.	Evaporation depth.	Evaporation (tank 7, 100 per cent).	Mean water temperature.	Evaporation depth.	Evaporation (tank 7, 100 per cent).	Mean water temperature.	Evaporation depth.	Evaporation (tank 7, 100 per cent).	Mean water temperature.	Evaporation depth.	Evaporation (tank 7, 100 per cent).	Mean water temperature.			
1915.	*In.*	°F.	*In.*	*P. c.*	°F.	*In.*	*P. c.*	°F.	*In.*	*P. c.*	°F.	*In.*	*P. c.*	°F.	*In.*	*P. c.*	°F.	°F.	*P. c.*	*Miles.*
Nov. 22	0.69	.....	0.73	106	.....	0.64	93	.....	0.71	103	.....	0.86	125	.....	0.96	139	.....	40.6	.....	1,112
29	.70	.....	.73	104	.....	.81	115	.....	.91	130	.....	1.01	144	.....	1.21	173	.....	38.8	.....	1,015
Dec. 6	.25	.....	.27	108	.....	.29	116	.....	.30	120	.....	.32	128	.....	.48	192	.....	38.8	.....	633
13	.43	.....	.42	98	.....	.45	105	.....	.52	121	.....	.55	128	.....	.68	158	.....	39.5	.....	518
1916.																				
Feb. 28[a]	1.21	.....	1.20	99	.....	1.49	123	.....	1.82	.....	.....	1.63	135	.....	1.91	158	.....	.....	.....	.....
Mar. 6	.67	.....	.71	106	.....	.73	109	.....	.77	115	.....	.86	128	.....	.98	146	.....	39.3	.....	853
13	.73	.....	.65	89	.....	.82	112	.....	.89	122	.....	.95	130	.....	1.17	160	.....	46.3	.....	1,273
20	1.00	.....	1.05	105	.....	1.17	117	.....	1.22	122	.....	1.31	131	.....	1.57	157	.....	49.5	.....	731
27	.63	47.6	.64	101	47.8	.72	114	47.5	.76	120	.....	.83	132	47.5	.85	135	.....	46.4	.....	1,022
Apr. 3	.77	47.2	.80	104	48.1	.90	117	48.2	.91	118	46.7	1.07	139	46.9	1.25	162	.....	42.6	.....	807
10	.49	45.8	.51	104	46.2	.60	123	46.0	.52	107	45.7	.65	133	46.8	.59	120	.....	36.4	.....	657
17	.87	52.2	.94	108	52.3	.99	114	51.4	.97	112	51.2	1.09	125	51.8	1.37	158	.....	48.3	.....	897
24	1.04	53.5	1.04	100	53.2	1.18	113	52.4	1.17	113	52.0	1.27	122	52.2	1.48	142	.....	48.7	.....	785
May 1	1.09	54.7	1.16	106	54.7	1.18	108	53.5	1.28	118	53.5	1.32	121	54.0	1.55	142	.....	46.4	.....	870
8	1.19	56.0	1.18	99	56.3	1.33	112	54.7	1.34	113	54.2	1.53	129	55.0	1.66	139	.....	53.9	.....	860
15	1.65	.....	1.69	102	56.5	1.75	106	55.7	1.81	110	56.1	1.96	119	53.7	2.20	133	.....	50.5	60	1,189
22	1.01	53.8	.95	94	54.3	.99	98	.....	1.22	121	53.3	1.24	123	53.3	1.27	126	.....	48.2	71	819
29	2.06	61.2	2.04	99	58.9	2.12	103	60.7	2.45	119	60.0	2.54	123	60.5	2.91	142	.....	58.1	48	1,190
June 5	1.71	66.6	1.77	103	.....	1.89	110	65.2	2.07	121	.....	2.10	123	64.9	2.60	152	.....	61.7	56	634
12	1.61	65.8	1.56	97	.....	1.75	109	64.8	2.13	132	.....	2.05	127	65.0	2.49	154	.....	60.9	62	737
19	1.48	70.4	1.61	109	.....	1.65	110	69.0	1.80	122	.....	1.84	124	69.0	2.41	163	.....	65.0	54	613
26	2.21	69.3	2.24	101	.....	2.36	107	68.0	2.71	123	.....	2.66	120	69.6	3.62	164	.....	67.0	45	834
July 3	2.18	73.2	2.03	93	.....	2.42	111	72.0	2.75	126	.....	2.74	125	76.6	3.53	162	.....	73.5	47	774
10	2.18	73.0	2.09	96	.....	2.29	105	.....	2.68	123	.....	2.69	123	.....	3.54	162	.....	73.6	58	941
17	1.58	.....	1.54	97	.....	1.73	109	.....	1.89	120	.....	2.06	130	.....	2.64	167	.....	69.3	66	500
24	1.83	.....	1.84	100	.....	1.95	107	.....	2.11	115	.....	2.30	125	.....	2.88	137	.....	72.8	61	590
31	1.76	.....	1.72	98	.....	1.93	110	.....	2.08	118	.....	2.26	126	.....	2.76	157	.....	72.7	69	642
Aug. 7	1.40	.....	1.38	99	.....	1.38	99	.....	1.45	104	.....	1.64	117	.....	1.90	140	.....	68.8	78	532
14	1.43	.....	1.48	103	.....	1.54	108	.....	1.51	106	73.8	1.75	122	.....	2.24	157	.....	68.9	71	634
21	1.70	.....	1.69	100	.....	1.83	108	.....	1.96	115	.....	2.15	126	.....	2.57	151	.....	67.2	60	755
28	1.47	.....	1.47	100	.....	1.54	105	.....	1.79	122	.....	1.88	128	.....	2.05	140	.....	62.8	61	620

Sept. 4	1.57	.....	1.63	104	.....	1.69	108	.....	1.90	121	.....	2.17	138	.....	2.67	170	.....	65.5	44	622
11	1.82	.....	1.85	102	.....	2.01	110	.....	2.32	128	.....	2.44	134	.....	2.48	136	.....	60.9	51	882
18	.98	.....	1.05	107	.....	1.17	121	.....	1.22	124	.....	1.33	136	.....	1.64	167	.....	53.2	65	571
25	1.03	.....	1.07	104	.....	1.25	121	.....	1.41	137	.....	1.57	152	.....	1.72	167	.....	58.5	58	555
Oct. 2	1.15	.....	1.18	103	.....	1.28	111	.....	1.46	127	.....	1.48	129	.....	2.22	193	.....	50.5	56	588
9	1.11	.....	1.17	105	.....	1.30	117	.....	1.59	143	.....	1.59	143	.....	1.96	177	.....	51.0	64	849
16	.63	.....	.64	101	.....	.70	111	.....	.76	121	.....	.84	131	.....	1.07	170	.....	44.7	70	824
23	.24	47.0	.25	104	.....	.27	113	47.4	.29	121	48.0	.32	133	.....	.39	162	.....	39.6	73	712
30	.33	44.8	.29	88	.....	.35	106	45.8	.41	124	46.6	.44	132	.....	.59	179	.....	42.8	67	555
Nov. 6	.90	46.7	.99	110	.....	1.00	111	44.4	1.07	119	47.3	1.33	148	.....	1.41	157	.....	51.2	48	700
13	.38	42.6	.38	100	.....	.43	113	39.6	.47	124	41.4	.50	132	.....	.71	187	.....	27.7	70	820
Totals and percentages for year	49.16	.....	49.63	100.9	.....	53.87	109.6	.....	59.40	120.9	.....	63.12	128.7	.....	76.18	154.9	.....	.....	.....	.....
Totals and percentages for period Mar. 6–Nov. 13	45.86	.....	46.28	100.9	.....	50.19	109.5	.....	55.14	120.4	.....	58.85	128.3	.....	70.94	154.7	.....	.....	.....	.....
Mean weekly percentages for year	.....	.....	.....	101.3	.....	.....	110.2	.....	.....	120.8	.....	.....	130.1	.....	.....	156.5	.....	.....	.....	.....
Mean weekly percentages for periods Mar. 6–Nov. 13	.....	.....	.....	101.1	.....	.....	110.2	.....	.....	120.2	.....	.....	129.9	.....	.....	155.5	.....	.....	.....	.....

[a] The total for the period Dec. 13, 1915–Feb. 28, 1916, is shown under date of Feb. 28.

This same ratio holds true for the rim of metal projecting above the ground, mentioned previously. The concentration or radiation effect of this strip of metal is 12 times as great for the small tank as it is for the large one, in proportion to the exposed area of the water. Higher temperatures during the average day and lower temperatures during the average night are reached by the small tank than by the large one. The temperature means are nearly the same, that for the large tank being slightly greater. However, the effect of the higher day temperatures may possibly be greater than that of the lower night temperatures and make the net evaporation due to temperature effect alone greater from the small tank than from the larger. Results from a tank exposed on all sides (No. 8) having a mean temperature lower, a night temperature lower, and a much higher day temperature than No. 7, are consistent with the foregoing statement.

There may be an appreciable vapor blanket effect on evaporation tanks of the size experimented with. An air movement great enough to remove such a covering from a tank 1 foot in diameter would not so quickly change the air above a pan or tank 12 feet in diameter. To pass over the 12-foot diameter in the exact time that is required to pass over the 1-foot diameter would necessitate a wind velocity 12 times as great over the 12-foot tank as over the 1-foot tank, and this variation can not occur. The records of the actual wind velocity for the year show a low velocity of 11.9 miles in 12 hours, or approximately 1.5 feet per second. This occurred once. Eighteen 12-hour periods are recorded having a wind movement of 20 miles or less in 12 hours. The average for the year is 59.5 miles in 12 hours, or approximately 7.5 feet per second. At that rate the largest tank would have a complete change of air covering at intervals of 1.6 seconds. Whether or not this effect is appreciable in the amount of evaporation from tanks of the size used is as yet a matter of opinion. If it is appreciable, then the result would be that of increasing the evaporation from the small tank over that from the large one.

But one previous investigation which would give information as to the ratio sought in the research being described has been made. That was in connection with the extensive study made at Salton Sea for the determination of an evaporation law. In order to compare the results of that with those found at Denver the equipment is described (3, p. 1134):

> In order to test the ratio of evaporation from pans of different sizes, our records include the following combinations: (1) A 4-foot pan self-registered hourly and a 2-foot pan along side on the ground near Tower No. 1; (2) a ow of 3 pans, 2-foot, 4-foot, 6-foot in diameter, on a platform on Tower No. 3, about half a mile from shore, and as near the water as was practicable; (3) a row of 4 pans, 2-foot, 4-foot, 6-foot, 12-foot on a series of adjoining rafts floating in the Salt Creek slue in calm water. The ratios are

quite steady and the results have been incorporated into the final value of the coefficient.

where C_2=0.023 (1.23)^n for 4-hour intervals.

n =0 for large open water areas,
n =1 for 6-foot pans,
n =2 for 4-foot pans,
n =3 for 2-foot pans,
n =4 for ordinary dry air.

The value of the coefficient for n=1 is fairly well determined, and is interpolated for n=4. These should be further verified if possible.

It will be noted from this extract and by a reference to the original work (3) that the pans used are of the type that is almost entirely exposed. The sides of the pans on rafts may have been partly water-covered. The results are not exactly comparable with those obtained at the Denver laboratory; nor would it appear that they could be as safely extended to large water bodies. A comparison on the basis that the results from the 6-foot tanks of each investigation are the same is given in Table III.

TABLE III.—*Ratio of evaporation at the Denver laboratory and at Salton Sea*

Test.	Denver laboratory.	Salton Sea.
Ordinary dry air	.....	209
1-foot tank	155	.....
2-foot tank	129	163
4-foot tank	118	125
6-foot tank	110	110
9-foot tank	101	.....
12-foot tank	100	.....
Large open-water area	.....	87

The extension of the results obtained at the Denver laboratory to larger water surfaces is discussed later.

RELATION BETWEEN EVAPORATION FROM CIRCULAR TANKS AND SQUARE TANKS SET IN THE GROUND OF EQUAL EXPOSED WATER SURFACE

Tank 4 is circular, with a diameter of 3.39 feet and an area of 9.0 square feet; tank 3 is 3 feet square; tank 2 is circular, with a diameter of 2 feet and an area of 3.14 square feet; tank 15 is 1.77 feet square. All are 3 feet deep and are set in the ground. Table IV shows the evaporation figures for these tanks. Based upon the totals, the evaporation from the larger square tank is 102.7 per cent of that from the circular one of the same area; that from the other square one is 103.5 per cent of that from the circular one of the same exposed area. Based upon mean weekly averages, these figures are 104.7 and 104.9.

TABLE IV.—*Relation between evaporation from square and circular tanks of the same surface area and depth. All tanks 3 feet deep, set in ground 2.75 feet.*

Week ending—	Evaporation from tank 4.	Evaporation from tank 3.	Evaporation from tank 3 expressed as a percentage of that from tank 4.	Evaporation from tank 2.	Evaporation from tank 15.	Evaporation from tank 15 expressed as a percentage of that from tank 2.
1915.	*Inches.*	*Inches.*	*Per cent.*	*Inches.*	*Inches.*	*Per cent.*
Nov. 22	0.71	0.84	118			
29	.91	.99	108			
Dec. 6	.30	.29	97			
13[a]	.52	.45	87			
1916.						
Feb. 28	1.82	1.86	102			
Mar. 6	.77	.89	115			
13	.89	.92	103			
20	1.22	1.26	103			
27	.76	.76	100			
Apr. 3	.91	.97	107			
10	.52	.59	113			
17	.97	1.12	116			
24	1.17	1.20	103	1.27	1.25	99
May 1	1.28	1.33	104	1.32	1.36	103
8	1.34	1.48	110	1.53	1.52	99
15	1.81	1.91	105	1.96	2.07	106
22	1.22	1.11	91	1.24	1.18	95
29	2.45	2.46	100	2.54	2.69	106
June 5	2.07	2.11	102	2.10	2.34	111
12	2.13	2.03	95	2.05	2.22	108
19	1.80	1.90	106	1.84	1.93	105
26	2.71	3.01	111	2.66	2.80	105
July 3	2.75	2.92	106	2.74	2.79	102
10	2.68	2.79	104	2.69	2.92	109
17	1.89	1.99	105	2.06	2.05	100
24	2.11	2.34	111	2.30	2.28	99
31	2.08	2.16	104	2.26	2.35	104
Aug. 7	1.45	1.61	111	1.64	1.55	95
14	1.51	1.72	114	1.75	1.80	103
21	1.96	2.04	104	2.15	2.14	100
28	1.79	1.75	98	1.88	1.78	95
Sept. 4	1.90	2.05	108	2.17	2.20	101
11	2.32	2.17	96	2.44	2.47	101
18	1.22	1.29	106	1.33	1.39	105
25	1.41	1.39	99	1.57	1.62	103
Oct. 2	1.46	1.53	105	1.48	1.70	115
9	1.59	1.51	95	1.59	1.70	107
16	.76	.86	113	.84	.90	107
23	.29	.31	107	.32	.40	125
30	.41	.43	105	.44	.57	130
Nov. 6	1.07	1.23	115	1.33	1.40	105
13	.47	.50	106	.60	.63	105
Total[b]	59.40	62.07	104.5	52.09	54.00	103.7
Percentage[c]			104.9			104.9

[a] From Dec. 13, 1915, to Feb. 28, 1916, weekly records were not possible.
[b] Totals and percentages are based upon these totals.
[c] Mean weekly percentages.

In the case of the 9 square-foot area the ratio, perimeter divided by area, is 0.15 greater in the case of the square tank than for the circular one. This has apparently caused an increase in evaporation of 2.7 per cent. For the tanks of 3.14 square feet area there is a corresponding increase of 0.26 in the ratio and an increase of 3.5 per cent in evaporation.

Although these figures do not show the exact relation, the comparison between the results from round and square tanks is sufficient to show that the great difference in the ratio, perimeter to area, for tanks ranging from 1 foot to 12 feet in diameter has an important part in the difference in evaporation depths from these tanks. No difference in mean water temperature could be measured between tanks 2 and 15, and 3 and 4.

VARIATION OF EVAPORATION WITH DEPTH OF TANK SET IN THE GROUND

Tanks 18 to 22 and tank 3 are 2 feet in diameter. They range in depth of water from 0.25 foot to 5.75 feet. Tanks 16 and 17 are 6 feet in diameter and, taken with No. 5, the set of three range in depth of water from 0.75 foot to 2.75 feet. These two sets were installed quite late in the season (May 25), but the results are representative. Table V shows the weekly evaporation depths for the nine tanks and the ratio of the evaporation from the tanks of lesser depth to that from the deepest of each set, expressed as a percentage. It is quite evident that the difference in evaporation over the range of depths is due to temperature. During the months when the cooling effects of the night were not so great, the shallow tanks show the greater evaporation; but later, when the day temperatures and the heat storage of the shallow tanks are more than offset by the low night temperatures, the shallow tanks indicate a lesser evaporation.

This difference in evaporation is not great, but for general use a tank not less than 2 feet deep is recommended, since its contents will not become heated or cool as quickly as those of the shallower tank. The difference between the results from the 6-foot tank and the 3-foot one is so slight that under all ordinary conditions there is no necessity for using a tank deeper than 3 feet. The evaporation as measured from tanks from 2 to 3 feet in depth may be more safely extended to the reservoir than that from shallower tanks, since the deeper tanks operate more in accordance with the reservoir under natural conditions.

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TABLE V.—*Relative depths of evaporation from tanks of the same diameter and varying depths*

Week ending—	Tanks all 3 feet in diameter.											Tanks all 6 feet in diameter.					
	Evaporation from tank 18, water 5.75 feet deep.	Evaporation from tank 2, water 2.75 feet deep.	Evaporation from tank 2, expressed as a percentage of that from tank 18.	Evaporation from tank 19, water 1.75 feet deep.	Evaporation from tank 19, expressed as a percentage of that from tank 18.	Evaporation from tank 20, water 1.25 feet deep.	Evaporation from tank 20, expressed as a percentage of that from tank 18.	Evaporation from tank 21, water 0.75 foot deep.	Evaporation from tank 21, expressed as a percentage of that from tank 18.	Evaporation from tank 22, water 0.25 foot deep.	Evaporation from tank 22, expressed as a percentage of that from tank 18.	Evaporation from tank 5, water 2.75 feet deep.	Evaporation from tank 16, water 1.75 feet deep.	Evaporation from tank 16, expressed as a percentage of that from tank 5.	Evaporation from tank 17, water 0.75 foot deep.	Evaporation from tank 17, expressed as a percentage of that from tank 5.	Mean air temperature.[a]
1916.	*Inches.*	*Inches.*	*Per cent.*	*Inches.*	*Per cent.*	*Inches.*	*Per cent.*	*Inches.*	*Per cent.*	*Inches.*	*Per cent.*	*Inches.*	*Inches.*	*Per cent.*	*Inches.*	*Per cent.*	°*F.*
June 12	1.36	2.05	104	2.05	104	2.04	104	2.09	107	2.18	111	1.75	1.68	96	1.73	99	61
19	1.92	1.84	96	1.90	99	1.84	96	1.98	103	2.21	115	1.65	1.75	106	1.76	106	65
26	2.87	2.66	93	2.89	101	2.92	102	2.97	103	3.05	106	2.36	2.38	101	2.52	107	67
July 3	2.85	2.74	96	2.94	103	2.93	103	3.05	107	2.95	104	2.42	2.43	101	2.45	101	74
10	2.77	2.69	97	2.76	100	2.85	103	2.84	103	2.82	102	2.29	2.32	101	2.34	102	74
17	2.03	2.06	101	2.07	102	2.11	104	2.11	104	2.10	103	1.73	1.69	98	1.76	102	69
24	2.37	2.30	97	2.33	98	2.31	97	2.32	98	2.36	100	1.95	1.95	100	1.94	99	73
31	2.28	2.26	99	2.28	100	2.24	98	2.22	97	2.23	98	1.93	1.96	101	1.88	98	73
Aug. 7	1.69	1.64	97	1.61	95	1.69	100	1.78	105	1.69	100	1.38	1.41	102	1.40	101	69
14	1.74	1.75	101	1.76	101	1.72	99	1.76	101	1.85	107	1.54	1.53	100	1.56	101	69
21	2.07	2.15	104	2.04	99	2.04	99	2.03	98	2.05	99	1.83	1.78	97	1.75	96	67
28	1.85	1.88	102	1.76	95	1.69	91	1.73	94	1.72	93	1.54	1.52	99	1.49	97	63
Sept. 4	2.17	2.17	100	2.07	95	1.98	91	1.86	86	2.00	92	1.69	1.53	91	1.68	100	66
11	2.43	2.44	100	2.33	96	2.21	91	2.13	88	2.17	89	2.01	1.89	94	1.74	87	67
18	1.39	1.33	96	1.23	89	1.17	84	1.13	81	1.03	74	1.17	1.02	87	1.00	85	53
25	1.62	1.57	97	1.47	91	1.44	89	1.45	90	1.45	90	1.25	1.15	92	1.18	94	58
Oct. 2	1.53	1.48	97	1.50	98	1.42	93	1.39	91	1.37	90	1.28	1.18	92	1.14	89	50
9	1.59	1.59	100	1.52	96	1.42	89	1.44	91	1.38	87	1.30	1.19	92	1.16	89	51
Total	37.13	36.60	98.6	36.51	98.3	36.02	97	36.28	97.7	36.61	98.6	31.07	30.36	97.8	30.48	98.1	.....

[a] From maximum and minimum thermometers.

EVAPORATION FROM FLOWING WATER

Early in July tank 26 was installed. This and No. 15 are of equal depth and exposed water area. Installation was made so that the exposure would be similar. They were located about 25 feet apart. A motor-driven centrifugal pump kept the surface water of No. 26 flowing. No. 15 was motionless. Thermometers were placed in each tank. Owing to a lack of means of preventing slopping, a surface volocity of 1.44 feet per second was all that could be attained.

Table VI gives the results of this investigation. These final figures were arrived at after the application of a temperature correction. Data for making this correction were obtained by the use of the special set of tanks, No. 21, 23, 24, and 25. They are all of the same depth and diameter. By the immersion of electric-light bulbs in them, a variation of surface temperatures was obtained. The weekly data on this work are recorded in Table VI. Plate 36, *B*, shows one of these tanks.

TABLE VI.—*Relation between the amounts of evaporation from a tank of flowing water and a tank of still water; tanks of equal exposed area, depth, and similar exposure. Exposed water surface 1.77 feet square; depth of tank 3 feet*

Date.	Length of run.	Evaporation from tank 15, still water.	Evaporation from tank 26, flowing water. Corrected for temperature increase.	Surface velocity of flowing water.
	Hours.	*Inch.*	*Inch.*	*Feet per sec.*
July 13	12	0.15	0.17	0.68
17	12	.22	.23	.68
18	12	.16	.19	.68
19	5½	.04	.04	.84
20	12	.24	.22	.84
21	12	.32	.29	.84
22	12	.34	.32	.84
23	12	.25	.26	.84
29	6¾	.12	.20	.98
Aug. 1	12	.13	.16	.98
2	12	.21	.22	.98
July 24	12	.24	.32	1.05
24–5	11	.18	.25	1.05
25	12	.24	.30	1.05
26	12	.21	.27	1.05
Aug. 16	8½	.11	.12	1.11
17	12	.24	.30	1.44
Total [a]	.....	3.40	3.86	.....

[a] Ratio, $\frac{\text{flowing}}{\text{still}} = \frac{3.86}{3.40} = 1.072$.

However, for making the temperature correction on the flowing-water data the temperature figures of corresponding days were used and not averages. An example will illustrate the method; July 13 will be taken.

Observed mean temperature for tank 15, 75°; evaporation, 0.15 inch.
Observed mean temperature for tank 26, 85°; evaporation, 0.24 inch.
Observed mean temperature for tank 21, 75°; evaporation, 0.12 inch.
Observed mean temperature for tank 23, 81°; evaporation, 0.27 inch.
Observed mean temperature for tank 24, 85°; evaporation, 0.32 inch.
Observed mean temperature for tank 25, 93°; evaporation, 0.43 inch.

It happens in this case that no interpolation is necessary, since the exact temperature of tanks 15 and 26 are found in the other set. Whenever interpolation was necessary it was done by means of a curve. The increase in evaporation caused by the 10° from 75 to 85, tanks 21 and 24, is 45 per cent of that from the tank of lower temperature. By assuming that this relation holds for the other tanks the observed figures should be reduced by 45 per cent of 0.15 or 0.07 inch, or the corrected evaporation from tank 26 is 0.17 inch.

During the latter part of August tanks 67 and 68 were installed. The installation is shown in Plate 36, *A*. The velocities in this experiment also had to be kept low. Table VII gives the final results, the correction for temperature being made in the manner described above.

TABLE VII.—*Relation between amounts of evaporation from a tank of flowing water and a tank of still water; tanks of equal exposed area, depth of water, and with similar exposure. Exposed water surface 1 foot by 25 feet; water about 3 feet deep*

Date.	Length of run.	Evaporation from tank 68, still water.	Evaporation from tank 67, flowing water. Corrected for increased temperature.	Surface velocity of flowing water.
1916.	*Hours.*	*Inch.*	*Inch.*	*Feet per sec.*
Aug. 28	12	0.17	0.22	0.52
25	8	.13	.13	.62
Sept. 1	12	.24	.23	.65
Aug. 29	8½	.10	.11	.67
Sept. 7	6¾	.11	.11	.71
13	12	.22	.23	.72
16	5	.07	.07	.79
14	12	.11	.14	.81
Oct. 1	8	.11	.16	.84
Aug. 30	5¼	.10	.10	.88
Sept. 8	12	.37	.32	.94
2	12	.28	.32	.95
25	12	.14	.18	.95
Oct. 2	10	.13	.14	.96
Sept. 6	9½	.23	.26	1.07
7	8½	.18	.20	1.25
Total [a]	.....	2.69	2.92	.....

[a] Ratio, $\frac{\text{flowing}}{\text{still}} = \frac{2.92}{2.69} = 1.086$.

The figures show that for the first set of tanks evaporation from the flowing water was 107 per cent of that from the still water under exactly the same conditions. For the other set, a tank 25 feet long, the evaporation from the flowing water was 108 per cent of that from still water. While this experiment was limited because of the low water velocity, it would tend to show that evaporation loss from a canal would be slightly greater than from a still body of water under exactly the same conditions

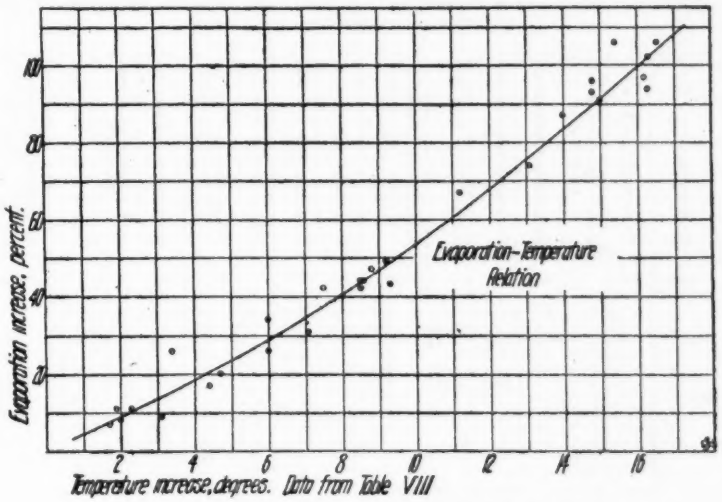

FIG. 5.—Relation of evaporation and temperature, all other factors being similar.

of exposure, temperature of water, etc. There seems to be no definite relation between evaporation and velocity within the limits of the experiment.

The only previous work in this connection noted is that carried out in Spain in 1849 (4), which for the short period of the experiment indicated an evaporation from moving water, agitated but not flowing, of 140 per cent of that from still water. Temperature effect was not considered in this, so far as can be learned.

EFFECT OF TEMPERATURE UPON EVAPORATION

As has been noted previously, the temperature effect upon evaporation was observed, primarily, for calibration by means of similar tanks heated to different temperatures. Thus, the variable is temperature, all other factors remaining the same. Figure 5 shows graphically the results indicated in Table VIII.

TABLE VIII.—*Relation of evaporation from small water surface to temperature of water surface, all other conditions being similar*

Week ending—	Evaporation from tank 21.	Mean temperature of water surface.	Evaporation from tank 23.	Mean temperature of water surface.	Degrees higher than No. 21.	Evaporation from tank 23, expressed as percentage of that from No. 21.	Evaporation from tank 24.	Mean temperature of water surface.	Degrees higher than No. 21.	Evaporation from tank 24, expressed as percentage of that from No. 21.	Evaporation from tank 25.	Mean temperature of water surface.	Degrees higher than No. 21.	Evaporation from tank 25, expressed as percentage of that from No. 21.
1916.	*In.*	°*F.*	*In.*	°*F.*		*Per ct.*	*In.*	°*F.*		*P. ct.*	*In.*	°*F.*		*Per ct.*
July 17	2.11	72.3	2.48	76.7	4.4	117	3.03	80.8	8.5	144	4.02	87.3	15.0	191
24	2.32	71.5	2.78	76.2	4.7	120	3.45	80.7	9.2	149	4.05	84.6	13.1	174
31	2.22	73.4	2.47	75.7	2.3	111	2.82	79.4	6.0	126	.....	.....	.....	.....
Aug. 7	1.78	71.7	1.94	74.8	3.1	109	2.33	78.8	7.1	131	2.54	81.0	9.3	143
14	1.76	72.1	1.95	74.0	1.9	111	2.94	83.3	11.2	167	3.66	86.5	14.4	208
21	2.03	69.8	2.24	71.5	1.7	107	2.73	75.8	6.0	134	3.92	84.6	14.8	193
28	1.73	67.8	1.86	69.8	2.0	108	.....	.....	.....	.....	3.57	83.2	15.4	206
Sept. 4	1.86	66.6	2.34	70.0	3.4	126	.....	.....	.....	.....	3.65	81.4	14.8	196
11	2.13	67.3	.....	.....	.....	.....	3.03	74.8	7.5	142	3.98	81.3	14.0	187
18	1.13	57.0	.....	.....	.....	.....	1.88	65.7	8.7	167	2.49	73.3	16.3	220
25	1.45	59.7	.....	.....	.....	.....	2.13	68.5	8.8	147	2.98	76.3	16.6	206
Oct. 2	1.39	56.5	.....	.....	.....	.....	1.97	65.0	8.5	142	2.70	72.8	16.3	194
9	1.44	54.2	.....	.....	.....	.....	2.08	62.8	8.6	144	2.83	70.4	16.2	197

In this connection attention is called to Table IX, showing temperatures at different points from the top to the bottom of the deeper tanks in use at the laboratory. The first set of temperatures recorded were early in the season, before the lower water had become warm, but on a warm day. The second measurement, on a cold day in May, shows how the whole water body has warmed up, and, though the air temperature is low, the heat storage effect of the water keeps its temperature above that of the air. Similar variations throughout the season are of interest. The temperature variations in the different-sized tanks are also brought out.

TABLE IX.—*Water temperatures at different depths in evaporation tanks and lake*

Date.	Depth below surface.	Air temperature.[a]	Water temperature (°F.).									
			Tank 7.	Tank 6.	Tank 5.	Tank 4.	Tank 2.	Tank 1.	Lake and tank 9.	Tank 18.	Tank 20.	Tank 22.
1916.	*Feet.*	°F.										
Mar. 27	0.05	69	59	60	62	61	63	.....	.....	.....	.....	.....
	.25	.....	53	56	56	56	58	.....	.....	.....	.....	.....
	.5	.....	49.5	53	50	50	51	.....	.....	.....	.....	.....
	.75	.....	48	49	47.5	48	47.5	.....	.....	.....	.....	.....
	1	.....	47	46	46	46.5	46	.....	.....	.....	.....	.....
	1.5	.....	46.5	45	44.5	46	45	.....	.....	.....	.....	.....
	2	.....	46.5	45	47	45.5	44	.....	.....	.....	.....	.....
	2.5	.....	46.5	44.8	44	45	44	.....	.....	.....	.....	.....
	2.75	.....	.....	.....	.....	45	44	.....	.....	.....	.....	.....
May 12	.05	45	.....	56	55.5	55	55	.....	.....	.....	.....	.....
	.25	.....	.....	56	55.5	55	55	.....	.....	.....	.....	.....
	.5	.....	.....	56	55.5	55.5	55	.....	.....	.....	.....	.....
	.75	.....	.....	56	55.5	55.5	55.5	.....	.....	.....	.....	.....
	1	.....	.....	56	55.5	55.5	55.5	.....	.....	.....	.....	.....
	1.5	.....	.....	56	55	55	54.5	.....	.....	.....	.....	.....
	2	.....	.....	56	55	55	54.5	.....	.....	.....	.....	.....
	2.5	.....	.....	56	55	55	54	.....	.....	.....	.....	.....
June 16	.05	73–76	71	72	.....	71.6	72.5	76.5	74	71.5	71.5	80.2
	.25	.....	69.5	70.1	.....	70.6	70	75	73.7	69.8	70	80.8
	.5	.....	69.3	70	.....	68.7	68	71	73.7	67.7	68.8	.....
	.75	.....	69	69.5	.....	68	67.5	69	73.7	.....	68.8	.....
	1	.....	69	69	.....	67.5	66.75	68	73.7	66.5	68.5	.....
	1.5	.....	69	68.8	.....	66.6	65.8	67	.....	66	.....	.....
	2	.....	69	68.8	.....	66.1	65.2	65.8	73.4	65.2	.....	.....
	2.5	.....	69	68.8	.....	66	64.8	65.3	.....	64.5	.....	.....
	3	.....	.....	.....	.....	.....	.....	.....	73	64	.....	.....
	4	.....	.....	.....	.....	.....	.....	.....	71	63.8	.....	.....
	5	.....	.....	.....	.....	.....	.....	.....	70.5	63.8	.....	.....
	6	.....	.....	.....	.....	.....	.....	.....	70	.....	.....	.....
	6.9	Bottom.	.....	.....	.....	.....	.....	.....	70	.....	.....	.....
June 29	.05	94	77.5	76.6	77.5	.....	81	.....	.....	.....	79	81
	.25	.....	77.5	77	78	.....	80.5	.....	76.8	.....	79.2	81.2
	.5	.....	77.5	77	78.2	.....	79.0	.....	76.8	.....	79.5	.....
	.75	.....	77.5	76.6	75.6	.....	77	.....	76.5	.....	79.5	.....
	1	.....	77.3	74.5	74	.....	75	.....	75	.....	79.5	.....
	1.5	.....	77.3	72.5	74	.....	73	.....	73	.....	.....	.....
	2	.....	77.3	71.5	73.5	.....	72	.....	72	.....	.....	.....
	2.5	.....	77.3	71	73.5	.....	71	.....	70.5	.....	.....	.....
	3	.....	.....	.....	.....	.....	.....	.....	70.5	.....	.....	.....
	4	.....	.....	.....	.....	.....	.....	.....	70	.....	.....	.....
	5	.....	.....	.....	.....	.....	.....	.....	69.8	.....	.....	.....
Sept. 1	.05	80–84	70	70	70	70.5	71.6	77	74	73	73.5	81.5
	.25	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	81.5
	.5	.....	69	69	68.4	68	69.4	72	72	72	70.6	.....
	.75	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
	1	.....	68	68	67.2	66.5	67	68.5	72	69	69.5	.....
	1.5	.....	68	67.5	66.5	65.6	66	67.5	72	68	.....	.....
	2	.....	68	67.5	66.2	65.4	65.2	66.7	71.5	67.2	.....	.....
	2.5	.....	68	67.2	66.2	65	65	66.5	70	66.5	.....	.....
	2.75	.....	68	67.7	66.5	65.5	65.5	66.5	.....	66	.....	.....
	3	.....	.....	.....	.....	.....	.....	.....	69.5	66	.....	.....
	4	.....	.....	.....	.....	.....	.....	.....	69	.....	.....	.....
	5	.....	.....	.....	.....	.....	.....	.....	69	.....	.....	.....
	6	.....	.....	.....	.....	.....	.....	.....	68	.....	.....	.....
	7.5	.....	.....	.....	.....	.....	.....	.....	67	.....	.....	.....
Sept. 27	.05	56	56.5	56.5	55.5	56	57.2	59	.....	.....	.....	.....
	.25	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
	.5	.....	57	57	55.7	56.2	57	59	.....	.....	.....	.....
	.75	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
	1	.....	57.2	57	56	56.2	57	59	.....	.....	.....	.....
	1.5	.....	57.3	57.1	56	56.5	57.1	59	.....	.....	.....	.....
	2	.....	57.4	57.2	56	56.5	57.2	59	.....	.....	.....	.....
	2.5	.....	58	57.7	58	56.5	58.5	59	.....	.....	.....	.....

[a] Temperature in instrument shelter.

UNITED STATES WEATHER BUREAU STANDARD PAN FOR CLASS A STATIONS

Plate 37, *A*, shows the United States Weather Bureau standard pan as specified for class A stations. This is also shown as *A*, figure 3. The

pan was installed in November, 1915, emptied for the winter, refilled in March, 1916, and used throughout the year ending in November, 1916. Table X presents figures from this pan in comparison with the evaporation with tank 7. Based upon the totals during the time of use of the pan, evaporation from it was exactly 1½ times that from the large pan sitting in the ground. In extension to large water surfaces this figure would be safe to use under conditions similar to those at Denver. However, since the pan departs so greatly from the reservoir, in that its whole water body is above the ground and is subjected to effects of radiation and heat concentration, no statement can be made regarding the application of the figure (1½) to other locations. Temperature records show a very much higher day temperature, a somewhat lower night temperature, and a lower mean temperature for this tank than any set in the ground. It follows more closely the variations in air temperature than any of the other tanks used except the very shallow ones.

TABLE X.—*Relation between evaporation from tank 7 (12 feet in diameter by 3 feet in depth, set in ground 2.75 feet) and a Weather Bureau standard pan (tank 8) for class A station, under same conditions*

Week ending—	Evaporation from tank 7.	Evaporation from tank 8.	Evaporation from tank 8, expressed as percentage of that from tank 7.	Week ending—	Evaporation from tank 7.	Evaporation from tank 8.	Evaporation from tank 8, expressed as percentage of that from tank 7.
1915.	*In.*	*In.*	*P. ct.*	1916.	*In.*	*In.*	*P. ct.*
Nov. 22	0.69	1.00	145	July 3	2.18	3.89	178
29	.70	1.23	175	10	2.18	3.04	140
Dec. 6	.25	.42	168	17	1.58	2.64	167
13 [a]	.43	.76	176	24	1.83	2.71	148
1916.				31	1.76	2.66	157
Mar. 6	.67	.99	148	Aug. 7	1.40	1.97	141
13	.73	1.21	166	14	1.43	2.09	146
20	1.00	1.78	178	21	1.70	2.37	139
27	.63	.98	156	28	1.47	1.92	131
Apr. 3	.77	1.03	136	Sept. 4	1.57	2.24	143
10	.49	.63	129	11	1.82	2.45	135
17	.87	1.53	176	18	.98	1.33	136
24	1.04	1.55	144	25	1.03	1.80	175
May 1	1.09	1.59	146	Oct. 2	1.15	1.54	133
8	1.19	2.05	172	9	1.11	1.63	147
15	1.65	2.19	133	16	.63	1.09	174
22	1.01	1.49	148	23	.24	.36	150
29	2.06	2.89	140	30	.33	.50	151
June 5	1.71	2.50	146	Nov. 6	.90	1.30	145
12	1.61	2.27	135	13	.38	.60	158
19	1.48	2.42	163	Total [b]	47.95	71.95	.....
26	2.21	3.31	150				

[a] Record broken. No. 8 was emptied on December 14 because of ice, and filled on February 29.
[b] Total evaporation from tank 8 expressed in percentage of that from tank 7, 150.0. Mean weekly percentage, 151.8.

PICHE EVAPORIMETER

The Piche evaporimeter used is of the so-called improved type, having a vent tube through the center opening at the top. It is graduated in cubic centimeters, having a capacity of 40 c. c. The glass plate is 9 cm. in diameter. It was hung in the instrument shelter.

Table XI shows the evaporation figures resulting from its use. These were not reduced to actual depths. A direct ratio between the evaporation (in cubic centimeters) from the Piche instrument and tank 7 was found in order to show the consistency of the results. Wind velocities seem to have no direct bearing on this ratio.

Previous experiments (1, p. 254) have been such as to warrant the statement, "Estimated its accuracy as correct within 20 per cent." The data of the writers tend to show that the statement is not too conservative. Its use is not recommended when another type of evaporimeter can be used, as it requires attention at more frequent intervals than other types of evaporation-measuring devices. On particularly dry days the tube would be empty within six hours after filling, and at such times, while the tube contained water, this water could not flow to the filter paper surface fast enough to prevent the drying and curling of the edge.

TABLE XI.—*Relation between evaporation from water surface tank 7 (12 feet in diameter by 3 feet in depth) and the Piche evaporimeter, Weather Bureau type*

Week ending—	Evaporation from tank 7.	Evaporation as shown by Pische mevaporieter.	Pische evaporation record +depth from No. 7.	Variation from mean ratio.	Wind movement.
1916.	*Inches.*	*C. c.*		*P. ct.*	*Miles.*
Apr. 24 [a]	1. 04	187. 0	180	− 0. 9	860
July 24	1. 83	368. 9	201	+10. 6	590
31	1. 76	319. 4	180	− .9	642
Aug. 7	1. 40	181. 8	130	−28. 5	532
14	1. 43	223. 8	156	−14. 2	634
21	1. 70	280. 8	165	− 9. 2	755
28	1. 47	217. 6	148	−18. 6	620
Sept. 4	1. 57	328. 8	209	+15. 0	622
11	1. 82	361. 0	198	+ 9. 5	882
18	.98	156. 0	159	−12. 5	571
25	1. 03	266. 2	259	+42. 6	555
Oct. 2	1. 15	225. 7	196	+ 7. 9	588
Total [b]	17. 18	3, 117. 0	[c] 181. 7	.....	.....

[a] Records broken until July 17.

[b] Ratio of totals, $\frac{3117.0}{17.8} = 181.3$.

[c] Mean weekly ratio.

EXTENSION OF THE EVAPORATION DEPTHS FROM LAND PANS TO LARGER OPEN-WATER SURFACES UNDER THE SAME CONDITIONS BY USE OF A FLOATING PAN

A part of Washington Park, South Denver, is shown in figure 1. The lake is artificial, material from the excavation having been taken to form an embankment for the west and southwest sides. The other shores are natural. The water level is maintained by the supply from the city ditch. There is no outlet, but seepage is great. It has been the custom to cut off the water supply late in the fall, and by spring, when water was again turned in, but a small pond would be left. The area of the lake is about 17 acres; the depth at the south and southeast is 3 to 4 feet and 5 to 8 feet north of the island; a maximum of 7.6 feet was measured at the point indicated by the star.

The contours give an idea of the exposure; some groups of trees are located about the lake, but these are still small. Plate 37, *B*, looking southeast, shows the character of these tree obstructions. The mean elevation of the water surface was for the season, 5,310.3 feet, or 36 feet lower than the highest point of the laboratory.

Evaporation tank 9, United States Geological Survey floating standard, was installed as soon as water was let into the pond in the spring, and the records show the dates of its use. The pan itself floated free in a 6-foot inclosure of the protecting raft. This raft was 16 feet square and was built of 8-inch material standing on edge. It proved an effective baffle for the wave action on this small reservoir. Four casks, one at each corner, were necessary, as the lumber became water soaked toward the end of the season. The raft, with floating tank, anemometer, and rain gage, was anchored at the point indicated by the star, 3,400 feet from the laboratory. The tank was reached by canoe. Observations were made on water temperature, wind, precipitation, and evaporation. No boats are allowed on the lake, and swimmers are not permitted to use it; thus, the evaporation pan was free from interference. Plate 37, *B*, shows a still well; this was later removed (after two weeks' use), and observations were taken when there was little wind movement.

Tabulated results of the season's observations are given in Table XII.

Evaporation as measured from the floating pan was for the season, 108.9 per cent of that from the 12-foot land pan at the laboratory and 86.1 per cent of that from a 3-foot square pan (equal in area and of similar shape to the floating) at the laboratory.

TABLE XII.—*Relation between evaporation from United States Geological Survey standard floating pan and land pans*

Week ending—	Evaporation from tank 7, land.[a]	Mean temperature of water at surface, No. 7.	Evaporation from tank 3, land.[b]	Evaporation from tank 3 expressed as a percentage of that from No. 7.	Mean temperature of water at surface, No. 3.	Evaporation from tank 9.[c]	Evaporation from tank 9 expressed as a percentage of that from No. 7.	Mean temperature of water at surface, No. 9.	Evaporation from tank 3 expressed as a percentage of that from No. 9.	Wind movement on lake.	Wind movement at laboratory.
1916.	*Inches.*	*° F.*	*Inches.*	*Per cent.*	*° F.*	*Inches.*	*Per cent.*	*° F.*	*Per cent.*	*Miles.*	*Miles.*
Apr. 24	1.04	53.5	1.20	115	52.0	1.04	100	.....	115	820	785
May 1	1.09	54.7	1.33	122	53.8	1.13	104	.....	118	926	870
8	1.19	56.0	1.48	124	53.7	1.15	97	58.2	129	928	860
15	1.05	.....	1.91	116	55.6	1.66	100	59.5	115	1,212	1,189
22	1.01	53.8	1.11	110	52.9	1.01	100	56.3	110	982	819
29	2.06	61.2	2.46	119	59.8	2.10	102	.....	117	.....	1,190
June 5	1.71	66.6	2.11	123	64.0	1.95	104	.....	108	715	634
12	1.61	65.8	2.03	126	63.5	1.78	107	67.2	117	778	737
19	1.48	70.4	1.90	128	67.4	1.75	118	70.2	108	691	613
26	2.21	69.3	3.01	136	66.7	2.45	111	70.1	123	723	834
July 3	2.18	73.2	2.92	134	71.6	2.46	113	79.5	119	704	774
10	2.18	73.0	2.79	128	71.4	2.50	115	74.1	111	905	941
17	1.58	.....	1.99	126	72.0	1.75	111	74.5	114	496	500
24	1.83	.....	2.34	128	72.0	2.02	110	75.7	116	597	590
31	1.76	.....	2.16	123	73.5	2.14	121	76.3	101	673	642
Aug. 7	1.40	.....	1.61	115	72.6	1.56	111	74.9	103	603	538
14	1.43	.....	1.72	120	72.2	1.57	110	75.8	109	619	634
21	1.70	.....	2.04	120	71.1	1.74	102	74.2	117	689	755
28	1.47	.....	1.75	119	68.7	1.57	107	71.7	111	635	620
Sept. 4	1.57	.....	2.05	131	67.4	1.70	108	68.8	120	672	622
11	1.82	.....	2.17	119	68.3	1.96	108	68.6	111[a]	1,470	882
18	.98	.....	1.29	132	58.6	1.06	108	64.2	122	.....	571
25	1.03	.....	1.39	135	60.7	1.13	110	62.6	123	531	555
Oct. 2	1.15	.....	1.53	133	57.7	1.37	119	59.3	112	632	588
9	1.11	.....	1.51	136	55.9	1.14	102	56.7	132	840	849
16	.63	.....	.86	137	50.3	.67	106	50.7	128	780	824
23	.24	.....	.31	129	48.3	.27	113	48.0	115	.....	712
30	.33	44.8	.43	134	46.7	.36	109	45.5	120	.....	555
Nov. 6	.90	46.7	1.23	137	46.7	.98	109	49.0	126	.....	700
Totals and percentages based upon these totals[d]	40.34	.....	50.63	125.5	.....	43.92	108.9	.....	.....	.....	.....
Mean weekly percentages	.....	.....	.....	126.0	.....	.....	108.1	.....	116.1	.....	.....

[a] Diameter, 12 feet, and 3 feet deep, set in ground 2.75 feet.
[b] 3 feet square by 3 feet deep, set in ground 2.75 feet.
[c] United States Geological Survey standard floating pan, on near-by lake, 3 feet square by 1.5 feet deep.
[d] Total evaporation from tank 3 expressed as a percentage of the total from No. 9 $= \frac{50.63}{43.92} \times 100 = 115.3$.

Figure 6 shows the relative temperatures of air (in instrument shelter), surface of water in tank 3, surface of water in tank 7, surface of water in tank 9, and the lake. Observations were taken both of the water in the tank at the lake and the lake water itself. The means were invariably the same, but occasionally the tank water would become 1 degree colder at night and 1 degree warmer during the day. No greater difference than 1 degree occurred. The difference is evidently due to influence of the radiation and concentration of the metal float tubes and the metal of the tank itself. The effect of heat storage is shown by the mean temperature curve; also the greater influence of the warm days over the cool

nights. Tank 3 has the low mean temperature; tank 7 comes between No. 3 and the lake, which is high. Figure 5 shows the influence of heat upon evaporation pans 2 feet in diameter under exactly the same conditions otherwise. There is no reason to believe that this relation would not extend to surfaces of larger water bodies of the same type. The curve would indicate that an increase of one degree mean temperature, all other conditions being the same, would increase the evaporation approximately 5 per cent at Denver for the season under consideration. The mean temperature of the lake is approximately 1 degree higher than

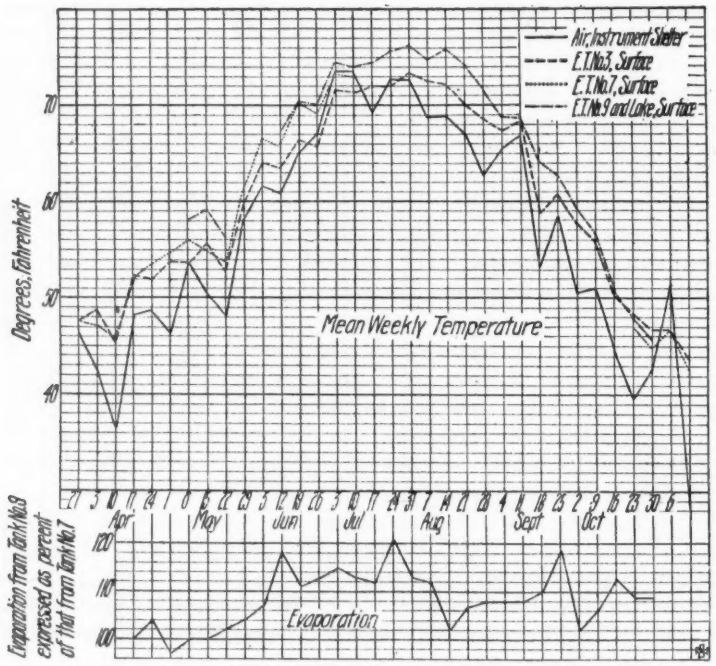

FIG. 6.—Relation of water and air temperatures.

that of tank 7. From that cause the lake evaporation would be then approximately 5 per cent more than that of tank 7. However, there is the ratio of perimeter to area, which would tend to make the lake evaporation less. The vapor-blanket effect mentioned previously would also lessen the lake evaporation in comparison with that from a land pan. The wind movement was practically the same at the lake as at the laboratory. A comparison between the 3-foot square tank at the laboratory and the floating tank would tend to strengthen the vapor-blanket theory. The mean temperature of the floating tank is higher, its wetted metal perimeter the same, yet its evaporation is less.

A careful consideration of all factors mentioned, and the curve (fig. 4) which is approaching the horizontal for the large areas, leads the writer to present the following conclusions:

(*a*) Evaporation figures from tanks 2 feet or greater in depth, preferably circular, set in the ground so that but a narrow metal rim not over 3 inches wide projects above the ground and in which water is kept approximately at the ground level, are most applicable for extension to large open-water surfaces.

(*b*) Data on such tanks may be quite safely extended to large open-water surfaces under exactly the same conditions of wind, air temperature, and relative humidity by multiplying the evaporation depth from a—

2-foot tank by 0.77	9-foot tank by 0.98
4-foot tank by 0.84	12-foot tank by 0.99
6-foot tank by 0.90	

Factors for depths from other tanks used have been found:

3 by 3 by 3 feet, sitting 2.75 feet in ground (Fort Collins type)	0.80
United States Geological Survey floating standard, 3 by 3 by 1.5 feet	.91
United States Weather Bureau for class A station, 4 feet in diameter, 10 inches deep, above ground	.66

These figures are not in agreement except in parts with those derived from previous work (8). However, it is quite certain that no previous investigation has gone into the problem in the manner of the one under discussion. The agreement between the results from a floating pan and a land pan of the same size is quite good; however, in many cases the description of the land pan does not state whether it was above the ground or set in the earth. It is quite probable that earlier figures obtained from the floating pan have been reduced too much in applying them to the reservoir itself. The tendency in comparing various records for floating and land pans has been to disregard the size of these pans. There are no data to show that the ratio existing between the figures from 3-foot land and floating pans would be the same as that from 6-foot land and floating pans. On the contrary, the great difference between the evaporation from land pans of 3 and 6 feet tends to show that the land-floating evaporation ratio is different for each size of pan.

METEOROLOGICAL OBSERVATIONS TAKEN IN CONNECTION WITH EVAPORATION INVESTIGATIONS IN GENERAL

In the course of the study the writer has, up to the present, referred to records in the original publications if possible, of evaporation measurements at 84 points in North America. It is the purpose to compile these in one table and present them to the public in a concise form if they can be correlated. In only a few instances have the figures been obtained

for purely scientific investigation; in most cases they were secured by engineers for immediate use in the study of a water supply and not under standard conditions, because there have been no standards. It is not strange that under these conditions the meteorological records are lacking. These evaporation depths undoubtedly served their purpose to the extent at least of satisfying the investigator. For the 84 stations, 31 have accompanying temperature figures, 9 relative humidity percentages, and 7 the wind movement. As they stand the records can be applied only under great disadvantage to other work, even in the same section. In many cases Weather Bureau records will supply part of the missing data which should accompany the evaporation figures proper, but not as satisfactorily as records taken at the evaporation station. It is obvious that Weather Bureau data, taken in a city, the station located on a roof, represent conditions which may differ greatly from those at a reservoir on which is floating an evaporation pan, though this reservoir may be but a few miles from the city station.

Factors which are at present believed to be the principal ones controlling evaporation are outlined. The effects of sunshine and radiation as measured by instruments for that purpose are understood even less than those of the so-called principal factors. There is, however, no proof that they are negligible, and a record of these may add to the value of future evaporation research.

TEMPERATURE

If water temperatures taken at the surface were available to accompany all evaporation measurements made, they would be of value. Evaporation research has proved that approximate calculation of amounts could be made from water temperatures alone. However, these data are to be had in connection with evaporation records in but few cases, and for estimating losses for districts where previous evaporation records have not been made water temperatures are never available. The increased value of the records justifies water-temperature measurements. Water temperatures are dependent upon air temperatures.

The long establishment and very complete records of the Weather Bureau make it possible to secure data on air temperature for all parts of the country, taken under standard and somewhat similar conditions (27). The advantage of a method of basing evaporation estimates upon these records is obvious. The publications of that Bureau present daily records arranged in periods of one calendar month. Mean temperatures are essential, and from the records means may be found for periods of any length. A month is too long, since there may be such variations during the period that the mean does not correctly define the conditions in their application to evaporation. One day is too short, since water-temperature variations lag behind those of air, and their effect may be shown several hours later on the evaporation record. Periods

of one week have been used in this investigation and are recommended. This statement is made with reference to the practical application of temperature data to evaporation estimates. For the much-sought evaporation law it is quite probable that the unit of time will be shorter. Means will probably not be used in the final solution of the problem, and the time interval will be reduced to minutes. However, then to apply this to field conditions and make use of the existing data the unit will be lengthened and the exact evaporation law (when that is finally discovered) may have to be approximated for practical application.

Registering maximum and minimum thermometer records are used in arriving at the weekly means. Their agreement with the mean as found by the use of the thermograph proves their reliability. A thermograph record sheet for one week is shown as figure 7. From it the maximum and minimum temperatures for each day have been taken and their means found. Table XIII, showing these figures and daily means found by integrating the thermograph curves, gives from the curve a weekly mean of 51° F.; by the other method 53°.

TABLE XIII.—*Analysis of temperature from thermograph record for the week of September 11–18, 1916.* (*See fig. 7*)

Day of week.	Temperature (°F.).			Mean obtained by planimeter from graph for 24 hours ending 7.00 a. m.
	Maximum for 24 hours ending 7.00 a. m.	Minimum for 24 hours ending 7.00 a. m.	Mean maximum + minimum ÷ 2 for 24 hours ending 7.00 a. m.	
Tuesday	50	39	44	43
Wednesday	72	44	58	57
Thursday	80	40	60	58
Friday	55	32	44	42
Saturday	68	39	54	50
Sunday	70	40	55	51
Monday	73	38	56	56
Mean for the week	.....	.....	53	51

WIND MOVEMENT

Practically all of the proposed evaporation formulas have included the wind factor. It is evident, that to be applicable directly, the wind movement figures used should represent that movement quite close to the water surface. The Weather Bureau records represent standard conditions as near as possible, but with the anemometer 18 to 30 feet above the building on which it is located, and that building of no standard height (26). Ordinarily these records will have to be reduced to apply them directly to evaporation estimation. At the Denver laboratory the records show for the period April 17 to October 31 an average velocity

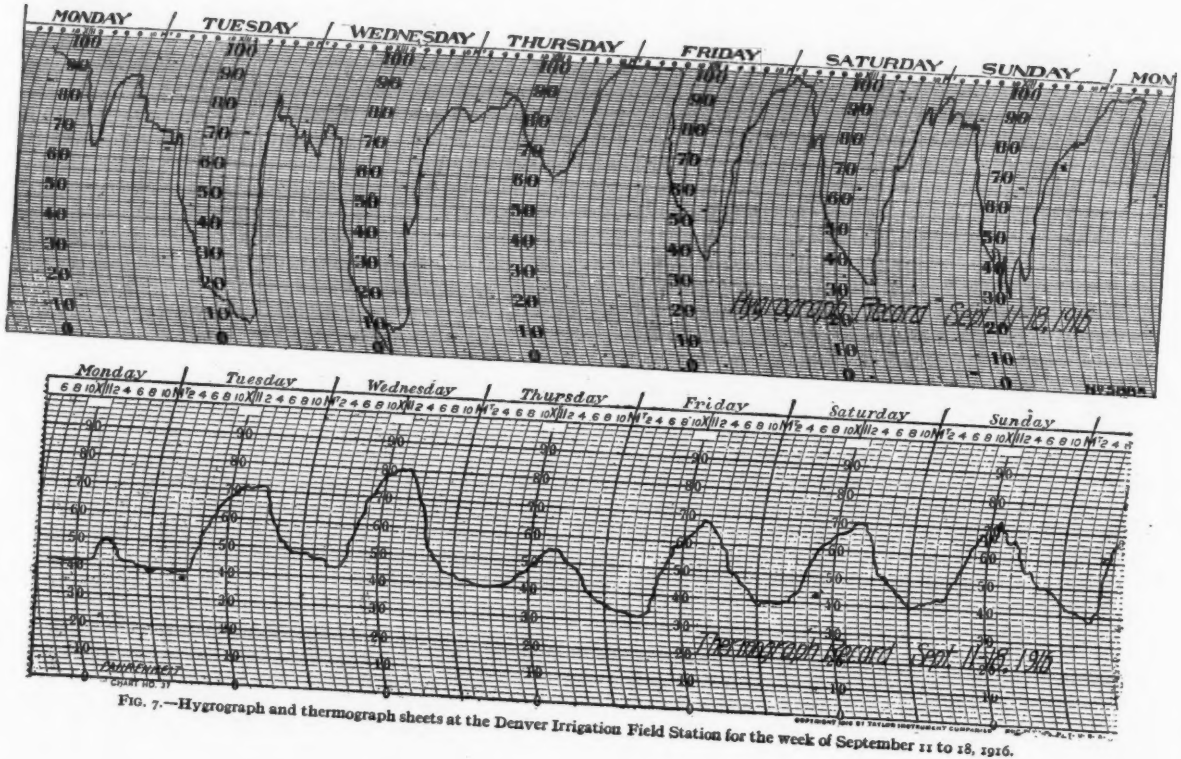

FIG. 7.—Hygrograph and thermograph sheets at the Denver Irrigation Field Station for the week of September 11 to 18, 1916.

of 7.4 miles per hour for anemometer 1, 14 feet above the ground, and 5.3 miles per hour for anemometer 3, 2 feet above the ground. The increase is 39 per cent. An investigation of the variation of wind velocity at different heights in connection with the Salton Sea investigation gave justification for the use of a formula which indicated that the velocity at a point, which from the beginning of the discussion referred to must have been 45 feet above the ground, was 141 per cent of the velocity at the bottom of the tower. This tower was fully exposed and free from interference to wind movement. The variation from the bottom of the tower to the top is shown as a straight line for all velocities (2, p. 30–31). Records giving a comparison between wind movements at the top of the Eiffel Tower, 984 feet, and the housetop level of Paris, probably less than 50 feet, indicate that the tower velocity is about four times that at the housetop level (14, p. 373).

Each evaporation observation station should have its own anemometer. Weather Bureau records of wind movement taken in connection with future evaporation measurements will probably give figures for the water surface, or approximately so (17).

RELATIVE HUMIDITY

An indication of the quantity of moisture mixed with the air is given by the relative humidity percentage. This, determined from the temperature of evaporation, should, in connection with other factors, be an index of evaporation depths from water surfaces. The term and its value are somewhat indefinite, being "relative." Taken in connection with the corresponding air temperature, the vapor pressure is obtained, which factor has been used in nearly all of the theoretical evaporation formulas proposed. Relative humidity figures or data form which to get these should accompany water surface evaporation studies. In many cases they do, usually taken, however, but once or twice a day. The use of the wet and dry bulb thermometer is doubtless the best method; however, a continuous record, by far the most valuable, is next to impossible by its use. The two readings a day method, however, gives an approximation to the integrated curve of the hygrograph, if the means are considered for a period of some length. As an illustration of this, a reproduction of the humidity record for one week is shown in figure 7 and the data are given in Table XIV.

The weekly mean from all 7 o'clock readings from this is 70 per cent. The integrated mean is 65 per cent. If but one reading a day is given, as is sometimes done, the variation is still greater, since the range during the day, particularly in this climate, is great. The hygrograph when properly adjusted and checked frequently with the psychrometer gives the most satisfactory record for evaporation use.

98976°—17——3

TABLE XIV.—*Analysis of relative humidity from hygrograph record for the week of September 11 to 18, 1916. (See fig. 7)*

Day.	Relative humidity (per cent).						
	Noon reading.	7 a. m. reading.	7 p. m. reading.	Mean from 7 o'clock readings.		Mean obtained by planimeter from graph.	
				Day.	Night.	Day.	Night.
Monday	89	89	82	86	66	80	76
Tuesday	17	50	36	43	52	21	68
Wednesday	10	67	43	55	64	21	78
Thursday	71	85	73	79	86	69	95
Friday	54	100	58	79	68	56	87
Saturday	45	79	58	68	70	45	82
Sunday	45	81	70	76	75	47	87
Monday	.....	80	.....	.....	.....	.....	.....
Weekly mean from noon readings	47	.....	.....	.....		.....	
Weekly mean from 7 a. m. readings	.....	79	.....	.....		.....	
Weekly mean from 7 p. m. readings	.....	.....	60	.....		.....	
Weekly mean from all 7 o'clock readings	.....	.....	.....	70		.....	
Weekly mean from the graph	.....	.....	.....	.....		65	

BAROMETRIC PRESSURE

Theoretically variations in atmospheric pressure as shown by the barometer should have an effect upon the rate of evaporation from water surfaces. With the variation of 1 inch at the Denver laboratory this effect could not be determined or even detected. It is quite probable that within the limits of variation of barometric pressure at any one station the effect of the variation is not material at the temperatures of the water bodies under investigation.

PART II.—EVAPORATION FROM THE SURFACES OF STREAM-BED MATERIALS

In many places the North Platte River, the South Platte River, the Rio Grande, and other western streams the water of which is used for irrigation have smooth and nearly level beds from ½ to 1 mile and over in width. Part of the year these may be covered with water; at other times the water table is below the surface of the sand. When they are covered, there is a loss going on from evaporation, but usually these floods occur at a season when evaporation rates are relatively low. Much of the time during the months when evaporation rates from a water surface are high the water table in the rivers is below the top of the sand. That there is a loss from this sand surface has not been questioned, but there have been no figures from which to estimate this loss.

If it is assumed that the bed of a stream is ½ mile wide, in a 2-mile length there is a square mile of exposed sand. If it is assumed that this is a water surface from which the evaporation is 40 inches a year, the loss for that year would amount to over 2,100 acre-feet. Even if the evaporation is only a small part of that, the loss is extensive over a 200 or 300 mile length of stream bed.

This evaporation can not be prevented, but it can be estimated quite accurately, provided basic data are available. These estimates are necessary in order to answer fairly questions pertaining to equitable division of water. So far as can be learned, only one previous investigation has been carried on the results of which may be applied to this problem.[1]

A study of this loss was made at the Denver Laboratory during the season 1916. In general, the method was the following: Typical stream-bed materials were secured; these were placed in water-tight tanks; the water table was held at certain fixed levels; the loss by evaporation was measured; the final figures for this loss are given as a percentage of the loss from a water surface.

RIVER-BED MATERIALS USED

At the beginning of the work samples of river-bed materials were secured from the principal streams. The specifications for the collection of these called for

> at least two samples, each of which will represent an average type of river bed material. These samples should be taken in a vertical section extending from the surface to the depth of 24 inches.

Each lot consisted of 20 pounds. Materials from 27 points, covering 16 different streams, were obtained. These are given in Table XV, with their numbers, location on the river, and the collector's name. This number will be used throughout the discussion.

[1] DIESEM, H. C. PRELIMINARY REPORT, PLATTE VALLEY INVESTIGATION. Unpublished.

TABLE XV.—*List of river-bed materials analyzed*

[Numbers refer to those given on diagrams and in other tables]

Sample No.	River and location.	Collector of sample.
1	South Platte, Denver, Colo., intersection of river and Vale Street, screened through ¼-inch revolving.	Commercial.
2	North Platte, south of Mitchell, Nebr.	H. C. Diesem.
3	Cache la Poudre, Colo., 300 feet W. of E. line of sec. 3, T. 7 N., R. 69 W., on an island.	R. G. Hemphill.
4	Cache la Poudre, just below Bellvue Bridge, sec. 30, T. 8 N., R. 69 W.	Do.
5	Cache la Poudre, Windsor, Colo.	Carl Rohwer.
6	Cache la Poudre, Greeley, Colo.	Do.
7	South Platte, 1 mile above mouth of Cache la Poudre.	Do.
8	South Platte, at Evans, Colo.	Do.
9	South Platte, at river bridge south of North Platte, Nebr.	H. C. Diesem.
10	Cherry Creek, intersection with Steele Street, Denver.	Commercial.
11	Arkansas, at Avondale, Colo.	J. M. Murtha.
12	Rio Grande, 1½ miles west of Mesilla, N. Mex.	D. W. Bloodgood.
13	Salt, near Mesa, Ariz.	P. E. Fuller.
14	Colorado, Imperial Canal intake.	F. J. Vielmeyer.
15	Santa Ana, Riverside, Cal., above West Riverside Bridge. A large part of this came out of Lytle Cañon, winter 1915–16.	W. W. McLaughlin.
16	Santa Ana, southeast of Fullerton, Cal.	Do.
17	San Joaquin, Cal.	R. D. Robertson.
18	Sacramento, Princeton, Cal.	Charles Kaupke.
19	Sacramento, Calusa, Calusa County, Cal.	Do.
20	Feather, N. line sec. 4, T. 18 N., R. 3 E., Mount Diablo base and meridian, Cal.	H. S. Patton.
21	Feather, S. line sec. 9, T. 16 N., R. 3 E., Mount Diablo base and meridian, Cal.	Do.
22	Columbia, 1 mile below mouth of Snake, near Burbank, Wash.	E. M. Chandler.
23	Umatilla, ¼ mile below Maxwell diversion dam, 9 miles from mouth of river, Oreg.	P. S. Jones.
24	Umatilla, ¾ mile above Maxwell diversion dam, 10 miles from mouth of river, Oreg.	Do.
25	Yakima, near Grandview, Wash.	J. G. Heinz.
26	Yakima, near Toppenish, Wash.	Do.
27	Sevier, Utah.	L. M. Winsor.

A mechanical analysis of each sand was made. The screens used were standard 8-inch diameter, of the following sizes, or mesh per inch: 1, 4, 12, 16, 20, 30, 40, 50, 60, 80, and 100. At least three 1,000-gm. runs were made on each sample, and in case of any practical variation the entire 20-pound lot was screened. The screens were handled by means of a mechanical shaker (23), and the percentage of voids was obtained by the usual water method. Table XVI gives the complete data of the analysis. The graphical representation of this is shown in figures 8 to 10.

TABLE XVI.—*Results of mechanical analyses of river-bed materials.* (*See fig. 8–10*)

[Numbers refer to those given in the list of materials]

PERCENTAGE RETAINED ON SCREEN

Screen No.	Material No.																										
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
1	0	0	5.8	0	22.5	29.8	2.5	2.4	0	0	0	0	25.1	Seeds and sticks up to screen 50	0	0	0	16.6	0	68.0	0	26.6	32.1	34.6	0	45.4	0
4	.4	0	6.0	31.1	18.4	19.0	17.7	24.8	0	0	0	0	15.4		0	7.0	0	39.3	0	19.5	0	35.1	36.4	41.4	0	30.3	0
12	37.5	16.1	3.5	31.6	6.9	12.9	21.3	26.9	32.4	13.0	[a] 2.2	0	9.3		0	9.2	0	14.9	0	4.6	0	7.5	10.7	6.3	.7	5.8	.5
16	12.7	8.4	.7	4.0	3.1	5.6	6.1	8.3	11.0	6.8	1.0	0	5.0		2.8	5.4	0	3.3	0	1.1	0	.3	2.4	1.2	.8	.9	1.0
20	8.9	7.2	.7	1.9	3.4	4.5	5.1	.7	9.8	6.9	4.2	0	5.4		1.8	5.6	.8	2.6	0	.9	0	.1	2.2	.9	1.2	.6	2.1
30	17.2	21.0	5.0	3.3	13.0	10.1	14.8	12.8	18.8	18.0	21.9	.1	15.5		10.6	18.6	.5	5.8	.2	1.7	.4	.2	4.1	2.3	9.4	1.5	18.2
40	10.2	17.7	11.1	5.2	12.4	5.6	15.6	8.7	13.2	17.0	24.3	.7	11.5		17.8	18.2	.7	3.9	.7	.9	1.0	1.2	2.9	2.0	35.0	2.2	32.3
50	5.3	9.9	10.7	5.9	6.4	3.1	9.3	4.3	6.6	13.0	13.6	5.5	5.6	.1	14.2	11.6	1.5	1.7	1.4	.6	2.0	4.2	1.9	2.0	25.0	2.1	19.6
60	2.9	7.0	11.7	5.9	4.0	2.3	4.3	2.7	4.1	9.6	9.1	16.5	3.0	.4	11.9	8.5	3.5	1.1	5.2	.5	5.2	6.0	2.0	2.0	16.7	2.2	13.7
80	2.2	5.8	14.1	4.8	2.5	1.4	2.0	1.8	2.5	7.5	6.7	35.2	1.5	1.5	12.0	6.4	13.5	1.1	34.8	.5	21.8	6.1	1.5	1.6	4.4	2.1	7.8
100	1.4	3.7	10.7	3.3	1.8	1.6	.8	.9	1.4	4.0	5.7	9.0	1.4	6.9	11.6	4.3	36.0	1.3	30.8	.4	47.8	5.6	1.1	1.9	3.0	2.1	3.3
Passing 100	1.3	3.2	18.9	2.7	5.4	3.5	.5	.7	.2	3.7	13.1	33.0	1.1	90.5	17.3	4.9	43.7	7.1	16.7	2.2	50.7	5.6	2.6	3.8	3.9	4.7	1.2

PERCENTAGE OF VOIDS

Composite material	43.7	35.3	39.2	35.3	[b]37.7	[b]31.9	35.8	35.4	32.0	39.2	37.6	41.4	[b]35.5	43.1	38.4	39.0	.....	.....	49.1	31.2	49.2	[b]37.6	[b]27.5	[b]31.7	.....	.....	.....
Passing 20, retained on 30	45.1	42.8	48.6	47.1	46.2	44.0	43.5	45.4	44.0	48.5	45.4	.....	44.9	.....	47.1	44.8	.....	41.5	.....	44.3	.....	.....	45.3	43.8	.....	.....	.....
Passing 60, retained on 80	45.2	46.0	47.4	50.2	47.2	47.5	47.3	47.4	43.7	50.1	45.7	46.3	46.9	52.9	47.8	46.8	.....	49.4	52.2	46.6	49.2	47.9	48.1	47.9	.....	.....	.....

[a] Sticks. [b] The large amount of coarse material made a screening necessary before an analysis for voids. This analysis was made on all passing screen 4.

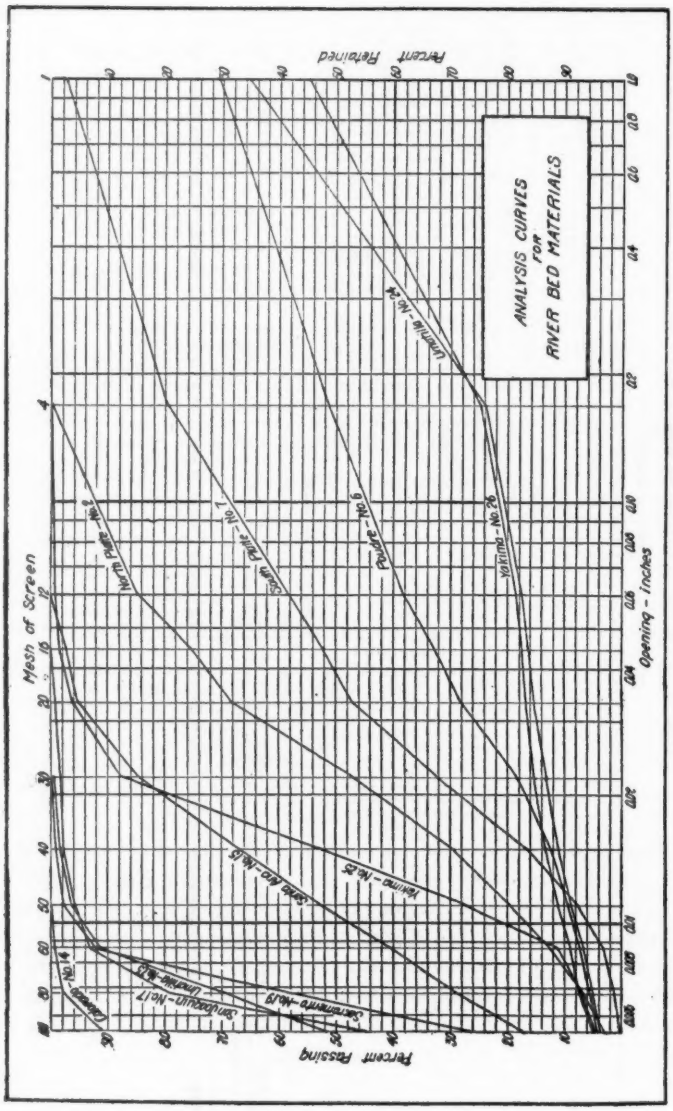

FIG. 8.—Analysis curves for river-bed materials from the Cache la Poudre, Colorado, North Platte, Sacramento, San Joaquin, Santa Ana, South Platte, Umatilla, and Yakima Rivers.

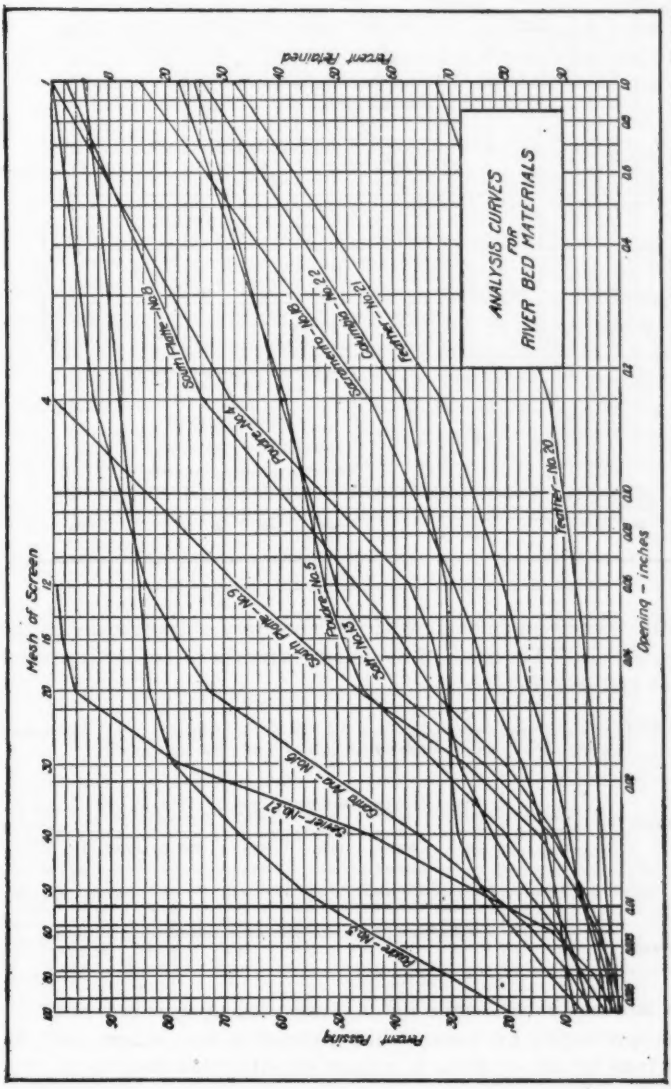

FIG. 9.—Analysis curves for river-bed materials from the Cache la Poudre, Columbia, Feather, Sacramento, Salt, Santa Ana, Sevier, and South Platte Rivers.

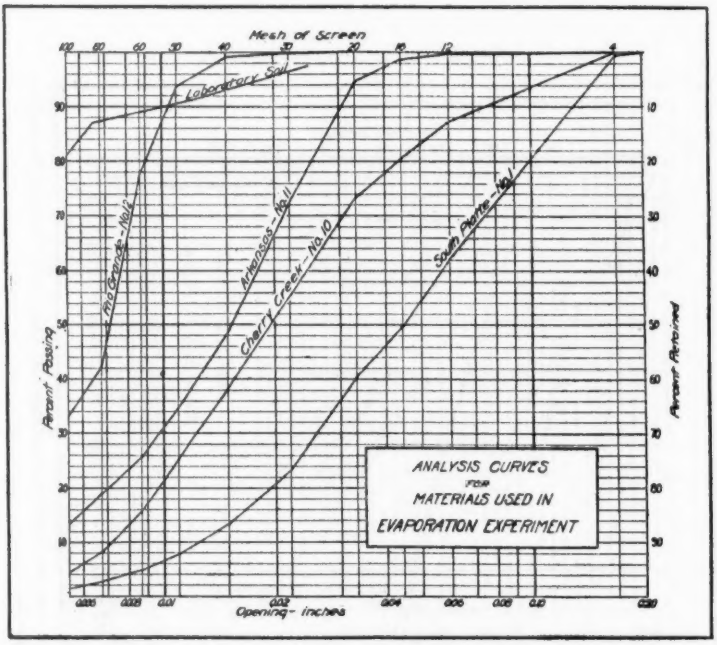

FIG. 10.—Analysis curves for materials used in evaporation experiment.

In this connection an analysis of the laboratory soil was made by the Bureau of Soils. The result of that analysis for the soil of the top 2 feet is given in Table XVII.

TABLE XVII.—*Mechanical analysis of the top 2 feet of the Irrigation Field Laboratory (Denver, Colo.) soil as made by the United States Bureau of Soils*

Depth	Organic matter.	Fine gravel (2–1 mm.).	Coarse sand (1–0.5 mm.).	Medium sand (0.5–0.25 mm.).	Fine sand (0.25–0.1 mm.).	Very fine sand (0.1–0.05 mm.).	Silt (0.05–0.005 mm.).	Clay (0.005–0.0 mm.).
Foot.	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*
1	0	1.0	6.8	5.9	39.0	20.9	14.6	11.9
2	0	3.6	5.7	3.0	30.6	20.2	17.1	19.8
Average	0	2.3	6.2	4.5	34.8	20.5	15.8	15.8

The laboratory soil, while not a water-washed river-bed material, offered opportunity for work with a material of fine texture; and the results from its use are given in connection with those from the strictly river-bed sands.

With the facilities and funds available it was not possible to make a complete investigation of each individual sand from the standpoint of

evaporation loss. Nor is it thought that such an investigation would have been of greater value than the one carried out. Typical sands to be used in the study were selected, No. 10 and 11 having a mean analysis curve, No. 12 representing a fine material, and No. 1 a coarse sand. Then in addition laboratory soil was used, this being of a still finer texture than No. 12.

EQUIPMENT

All records from water-surface evaporation tanks were taken, and all meteorological observations were made in connection with water-surface evaporation. No special apparatus was required for that. The equipment for the sand work consisted mainly of the Fortier type of water-jacketed tank (10, 11) shown as *D*, figure 3. Plate 38, *A*, shows the installation of these. Net losses from evaporation were determined by weight, the tanks being lifted to the platform scales in the manner shown in Plate 38, *B*. This motor-driven hoist runs on wood rails; its capacity is 2,500 pounds. Since the water levels were below the surface, a well (tin pipe 1 inch in diameter) was placed in each tank and the top closed with a cork stopper (Pl. 38, *A*). A description of the tanks is given in Table XVIII.

TABLE XVIII.—*Description of tanks used*

Tank No.	Diameter.	Depth.	Filled with sand No.	Water table.
	Inches.	*Feet.*		
27–28....	23.5	4	10	6 inches above the sand surface.
29–30....	23.5	4	10	3 inches above the sand surface.
31–32....	23.5	4	10	Surface saturated.
33–34....	23.5	4	10	3 inches below the sand surface.
35–36....	23.5	4	10	6 inches below the sand surface.
37–38....	23.5	4	10	12 inches below the sand surface.
39–40....	23.5	4	10	24 inches below the sand surface.
41–42....	23.5	4	12	3 inches below the sand surface.
43–44....	23.5	4	12	12 inches below the sand surface.
45–46....	23.5	4	11	Do.
47–48....	30.0	3	11	3 inches below the sand surface.
49–50....	30.0	3	1	Do.
51–52....	30.0	3	1	12 inches below the sand surface.
53.....	30.0	3	10	3 inches below the sand surface.
54.....	30.0	3	10	12 inches below the sand surface.
55–56....	23.5	1	(a)	4 inches below the surface.
57–58....	23.5	2	(a)	16 inches below the surface.
59–60....	23.5	3	(a)	28 inches below the surface.
61–62....	23.5	4	(a)	40 inches below the surface.
63–64....	23.5	5	(a)	52 inches below the surface.
65–66....	23.5	6	(a)	64 inches below the surface.

[a] Labaratory soil.

There were available 15 hoods for use in time of storm. These were used on tanks for which the correction necessary for the addition of storm water was difficult to make.

OBSERVATIONS

After the tanks were installed and filled, water was applied until a stable level was reached according to the schedule in Table XVIII. Tanks were weighed about twice each week, the platform scales weighing to ¼ pound. Observations were kept on the water level, a morning record being made, starting at 8 o'clock, and in the afternoon beginning at 3.30, for the greater part of the season. During particularly dry periods observations were started at 6.30 a. m., 12.30 p. m., and at 6.30 p. m. At the time of each observation of the level, additions of water were made in even pounds to bring it to the fixed elevation. The depth measurements were made to ¼ inch with an ordinary rule. Some difficulty was experienced in keeping the tanks having the surface saturated in exactly the right condition. After a couple of weeks' use these were provided with individual supply reservoirs which allowed a small quantity of water to drip into the tank. Very close attention was required. The entire water losses from the tanks were determined by the weighings and from the amount added to keep the level at the desired point.

DETAILED DATA AND FINAL RESULTS

The 14 tanks containing Cherry Creek sand were installed with a view to using them as a so-called standard from which to determine the general form of the curve of evaporation loss at different water levels. Five points were possible: saturation, water at 3 inches, at 6 inches, at 12 inches, and at 2 feet. It happened that the final figures showed that 10½ inches had been used instead of 12 inches. With the use of laboratory soil, which is not truly the same type of material, six points were found with the equipment, water at 4, 16, 28, 38, 43, and 51 inches. Of the other types used it was thought that, since the form of the evaporation curve could be learned from the so-called standards, two depths would present the desired information. Accordingly, for sands 1, 11, and 12, two depths, 3 and 12 inches, were used.

The detailed results of all observations have been tabulated. Sand 10 is covered in Table XIX. During the period July 31 to October 16 the final figures show the following results: At saturation the evaporation was 77 per cent of that from evaporation tank 2, a water surface tank of the same area with water 2.75 feet deep; 3 inches below the sand surface, 69 per cent; 6 inches, 64.5 per cent; 10½ inches, 57.7 per cent; and at 24 inches, 11.3 per cent. Table XX shows the data from laboratory soil; Table XXI that from sand 12, Rio Grande; sand 11, Arkansas, is tabuated as Table XXII; and No. 1, Platte, is shown on Table XXIII.

TABLE XIX.—*Actual evaporation from Cherry Creek sand, No. 10, with water table at different depths below the material surface. All tanks 1.96 feet in diameter*

Period ending [a]—	Actual depth of water evaporated (inches).					
	Evaporation from water surface tank 2 (2 feet diameter and 3 feet deep).	Water table below the sand surface.				
		0 (saturation).	3 inches.	6 inches.	10½ inches.	24 inches.
Aug. 4	1.01	0.45	0.62	0.67	0.50	0.19
9	1.12	1.23	1.07	.80	.74	.15
12	.85	.75	.90	.80	.69	.18
15	.69	.40	.35	.32	.28	.04
17	.54	.68	.34	.29	.21	.04
29	3.54	2.51	2.54	2.42	2.22	.80
Sept. 12	4.44	3.14	2.71	2.62	2.47	.34
25	2.83	2.34	2.16	2.06	1.82	.25
29	.91	.46	.42	.40	.36	.12
Oct. 4	1.23	1.06	.69	.67	.63	.00
10	.99	.51	.54	.54	.50	.00
16	.88	1.04	.62	.62	.50	.16
Total	18.93	14.57	13.06	12.21	10.92	2.27
Percentage [b]	100.0	77.0	69.0	64.5	57.7	11.3

[a] The period began on July 31, 1916. [b] Water surface taken as 100 per cent.

TABLE XX.—*Actual evaporation from laboratory soil with water table at different depths below the soil surface. Experimental tanks 1.96 feet in diameter*

Period ending [a]—	Actual depth of water evaporated (inches).						
	Evaporation from water surface of tank 2 (2 feet in diameter).	Water table below the soil surface.					
		4 inches.	16 inches.	28 inches.	38 inches.	43 inches.	50½ inches.
Aug. 30	3.84	2.98	2.69	2.19	1.23	0.24	0.19
Sept. 15	4.77	4.37	4.09	3.12	1.98	.37	.32
25	2.10	1.81	1.67	1.44	.30	.16	.16
29	.91	1.04	.84	.69	.43	.11	.16
Oct. 4	1.23	1.14	.97	.58	.30	.10	.10
Total	12.85	11.34	10.26	8.02	4.24	.98	.93
Percentage [b]	100.0	88.2	79.8	62.4	33.0	7.63	7.24

[a] The period began on Aug. 17, 1916. [b] Water surface taken as 100 per cent.

TABLE XXI.—*Actual evaporation from Rio Grande material, No. 12, with water table at different depths below the surface. All tanks 1.96 feet in diameter*

Period ending [a]—	Actual depth of water evaporated (inches).		
	Evaporation from water surface of tank 2 (2 feet in diameter, 3 feet deep).	Water table below the surface.	
		3 inches.	12 inches.
Aug. 12	0.85	0.93	0.73
15	.69	.39	.48
17	.54	.49	.30
29	3.54	2.89	2.64
Sept. 12	4.44	3.36	3.05
25	2.83	2.16	2.13
29	.91	.78	.55
Oct. 4	1.23	.83	.83
10	.99	.51	.58
16	.88	.71	.43
Total	16.80	13.05	11.72
Percentage [b]	100.0	77.0	69.8

[a] The period began on Aug. 9, 1916. [b] Water surface taken as 100 per cent.

TABLE XXII.—*Actual evaporation from Arkansas material, No. 11, with water table at different depths below the surface*

Period ending [a]—	Actual evaporation depth (inches).		
	Evaporation from water surface of tank 2 (2 feet in diameter, 3 feet deep).	Water table below sand surface.	
		3 inches.	12 inches.
		Tank 2.50 feet diameter.	Tank 1.96 feet diameter.
Aug. 29	3.54	2.09	1.94
Sept. 12	4.44	2.88	2.61
25	2.83	2.25	2.05
29	.91	.49	.49
Oct. 4	1.23	.79	.70
10	.99	.55	.56
16	.88	.57	.43
Total	14.72	[b] 9.62	8.78
Percentage [c]	100.0	70.0	59.6

[a] The period began on Aug. 17, 1916.
[b] 10.32 equivalent for tank 1.96 feet in diameter. See Table XXIV giving ratio for this correction.
[c] Water surface taken as 100 per cent.

TABLE XXIII.—*Actual evaporation from South Platte graded river-bed material, 1, with water table at different depths below the surface. All tanks 2.5 feet in diameter*

Period ending [a]—	Actual depth of water evaporated (inches).		
	Evaporation from water surface of tank 2 (2 feet in diameter, 3 feet deep).	Water table below the surface.	
		3 inches.	12 inches.
Aug. 9	1.12	1.00	0.74
12	.85	.68	.45
15	.69	.39	.18
17	.54	.42	.29
29	3.54	1.75	1.01
Sept. 12	4.44	2.52	.49
25	2.73	1.90	.72
29	.91	.59	.14
Oct. 4	1.23	.63	.06
10	.99	.51	.00
16	.88	.63	.17
Total	17.92	11.02	4.25
Equivalent for tank 1.96 feet in diameter	.....	[b] 11.82	[b] 4.58
Percentage [c]	100.0	66.0	24.2

[a] The period began on Aug. 4, 1916.
[b] See Table XXIV for ratio for this correction.
[c] Water surface taken as 100 per cent.

From the list of tanks used it will be seen that No. 53 is a duplicate of Nos. 33 and 34, and that No. 54 duplicates Nos. 37 and 38, with the exception that 53 and 54 are 30 inches in diameter, while the others are 23½ inches. From work on evaporation from water surfaces, the difference in evaporation depths due to difference in size of the evaporation pan has been noted. Data were not at hand to show whether or not this relation would hold for the sand tanks. Table XXIV gives the results from the sand tanks of two diameters. The final figures indicate that for the period of the sand-tank work the evaopration from the surface of the sand from the smaller tank, approximately 2 feet in diameter, was about 7½ per cent greater than from the larger tank. This figure does not check that found for the water tanks, the corresponding difference there being 3½ per cent. The data do not indicate the cause of this difference, but the assumption is that it is due to a temperature effect. It is probable that the moist sand acts in a different capacity as a heat reservoir than does a tank of water.

TABLE XXIV.—*Relation between evaporation from sand tanks 1.96 feet in diameter and tanks 2.50 feet in diameter, with water table at 3 and 12 inches below the surface of the material*

Period ending [a]—	Actual evaporation (inches).			
	Water table 3 inches below surface.		Water table 12 inches below surface.	
	Tank 1.96 feet diameter.	Tank 2.5 feet diameter.	Tank 1.96 feet diameter.	Tank 2.5 feet diameter.
1916.				
Aug. 9	1.07	0.83	0.74	0.69
12	.90	.71	.69	.59
15	.35	.26	.28	.27
17	.34	.47	.21	.38
29	2.54	2.22	2.22	1.91
Sept. 12	2.71	2.52	2.47	2.01
25	2.16	2.02	1.82	1.81
29	.42	.55	.36	.46
Oct. 4	.69	.79	.63	.55
10	.64	.59	.50	.55
16	.62	.63	.50	.45
Total [b]	12.44	11.59	10.42	9.67

[a] The period began on Aug. 4, 1916.
[b] The ratio of evaporation from the tank 2.5 feet in diameter to that from the tank 1.90 feet in diameter is $\frac{12.44}{11.59}=1.073$ for a 3-inch depth of water table and for 12-inch depth of water table it is $\frac{10.42}{9.67}=1.078$.

The figures found for this comparison are used in the manner of correction factors in placing all evaporation results from sand upon the basis of a tank 2 feet in diameter. In the tables where this correction is made note is made of the change.

Figure 11 shows graphically the data given in Tables XIX to XXIII. It will be noted that the general slope of the lines is the same throughout. The form for the laboratory soil is similar to that of sand 10, and it is safe to assume that this form would be shown if more points were available for sand 1, the coarsest material used. The results seem consistent, with this exception: The loss from the saturated surface of No. 10 is 77 per cent of that from the water surface, while an extension of the curve for laboratory soil would tend to indicate that at saturation the loss from this would be much greater than 77 per cent. That evaporation from saturated surfaces, under apparently the same external conditions, should vary with the material of that surface seems questionable. The detailed results from sand 10 show also the individual figures to be inconsistent in connection with the saturated condition, being either greater or less than from the water surface, the cause of which is not evident. This is not true of the other figures of the series on this sand.

As was noted earlier, some difficulty was experienced in maintaining a uniform saturated condition. At no time was an automatic device used

to control the water level; by the tank arrangement it was necessary to entirely cut off the supply at night. During a part of the time a midnight observation was made, but not through all the season. Occasionally a greater depth than was required would be applied to the tanks, resulting in an excess of perhaps ⅛ to ¼ inch, never greater. The net result for the end of the season and for any day of the season was saturation. As all of the work done was performed with more care than is ordinarily used, the only explanation for the apparent discrepancy has been given.

In the final curves the results of this saturated condition are not incorporated. Examination of streams shows that the bed is very rarely in that condition. Water may be flowing in measurable depths, from a very small part of an inch up, or the sand will be moist, with the water table below the surface at varying depths. The saturated condition is rare in the extreme.

Tanks with water at depths of 3 and 6 inches were maintained throughout the run of the other tanks. The results are not given, since in weighing water was spilled at different times before the weight had been taken. Figures for losses from these tanks, when known to be correct, corresponded almost exactly with those for tanks in the series of varying depths, tanks 18 to 22, inclusive.

With the detailed data and curves of figure 11, together with the analysis curves for the river-bed material to work with, it was necessary to devise a means of showing the evaporation results based upon the sand-analysis figures in order to make the data of maximum value. There are two indices in common use representing the type or classification of a particular sand: Effective size and uniformity coefficient. The advantage of basing evaporation losses from wet sands upon one of these was obvious. A determination of both effective size and uniformity of coefficient was made for the materials used in the tanks. The effective size apparently offered the greatest possibilities. However, the water losses did not follow this consistently; uniformity coefficient was not at all applicable. The 60 per cent size, used in arriving at the uniformity coefficient from the effective size, was found to be much better. It is a term and classification in quite common use, defined as: That size of grain of material such that in mechanical screen analysis 40 per cent of the material by weight is larger and 60 per cent is smaller than that size, or based upon screen opening, that size of opening such that 60 per cent of the material passes and 40 per cent is retained.

When evaporation amounts were plotted as ordinates upon this 60 per cent size as abscissæ, fair curves resulted. To place the data in shape for use, Table XXV was prepared.

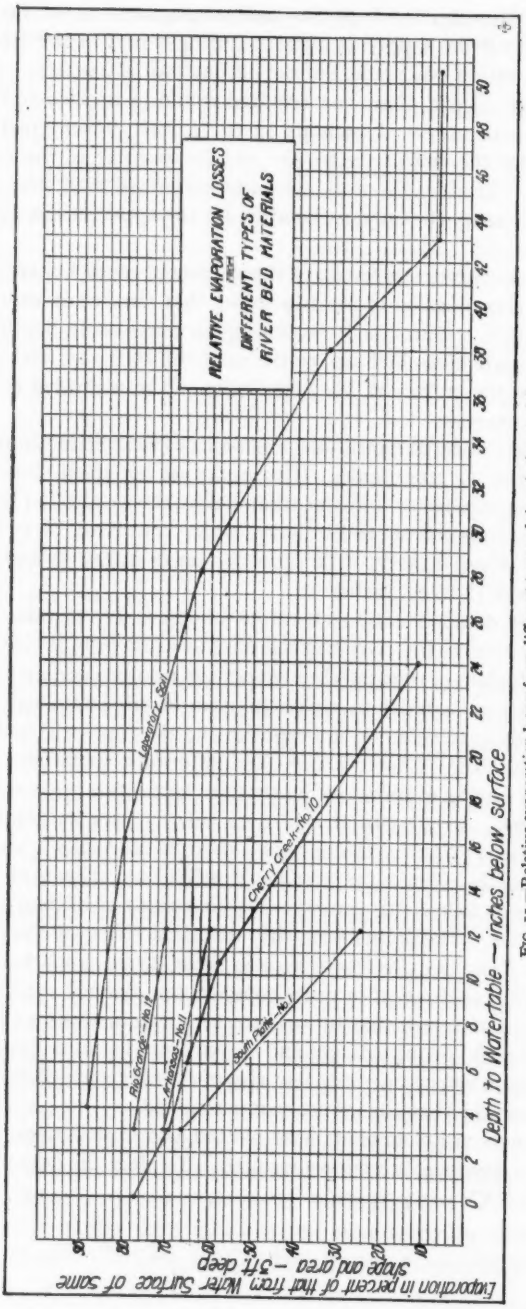
RELATIVE EVAPORATION LOSSES FROM DIFFERENT TYPES OF RIVER BED MATERIALS
Evaporation in percent of that from Water Surface of same Slope and area – 3ft. deep
Depth to Watertable – inches below surface
Lawrence C. Soil
Rio Grande – No. 11
Antelope – No. 1
Cherry Creek – No. 10
Rum Peke – No. 1

FIG. 11.—Relative evaporation losses from different types of river-bed materials.

TABLE XXV.—*Variation of evaporation loss from stream-bed materials, with size of sand grain—Water plane from 3 to 24 inches below the surface. (See fig. 11)*

Material used in experiment.	Effective size.	60 per cent size.	Uniformity coefficient.	Evaporation in percentage of that from free water surface of same shape and area, 3 feet deep, with a depth to water table of—				
				3 inches.	6 inches.	12 inches.	16 inches.	24 inches.
	Inch.	*Inch.*						
Laboratory soil	0.0001	0.003	3.00	[a]89	[a]86.6	[a]82.5	79.8	[a]68.0
Rio Grande 12	.0032	.0077	2.40	77	[a]74.5	69.8	.....	.....
Arkansas 11	.0049	.0180	3.68	70	[a]66.4	59.6	.....	.....
Cherry Creek 10	.0072	.0245	3.40	69	64.5	[a]53.0	[a]42.0	11.2
South Platte 1	.0152	.0570	3.75	66	[a]53.0	24.2	.....	.....

[a] Interpolated from figure 11. All other percentages are from Tables XIX to XXIII.

The evaporation percentages given include all the observed points shown in figure 11. Points interpolated from figure 11 are indicated. From this table figure 12 has been plotted. Observed figures are distinguished from the interpolated ones mentioned by the method of plotting.

Figure 13 shows the percentage of moisture in the top 4 inches of Laboratory soil with the water table at different depths. The upper curve, over the range of materials with 60 per cent size from 0.003 to 0.057 inch, indicates that with water 3 inches below the sand surface the loss by evaporation from this surface is from 89 to 66 per cent of that from a water surface of the same size and under the same external conditions. The graph shows these evaporation values for depths of water table from 3 to 24 inches, at 12 inches the range or loss being from 79 to 24 per cent, the greater loss in each case occurring from material of fine grain or texture.

TABLE XXVI.—*Factors for estimating evaporation losses from the surfaces of stream-bed materials*

[Multiply the evaporation from a water surface of the same size and similarly exposed by the factors given to get the evaporation from the sand surface]

Depth of water table below the surface.	Factor.				
	60 per cent size of the material (inches)—				
	0.01	0.02	0.03	0.04	0.05
Inches.	*Inch.*	*Inch.*	*Inch.*	*Inch.*	*Inch.*
3	0.74	0.69	0.69	0.68	0.67
6	.71	.66	.63	.59	.56
12	.67	.57	.49	.40	.30
16	.61	.47	.....	.....	.....
24	.44	.21	.....	.....	.....

One check upon this work has been found; in 1915 Diesem at North Platte found that the evaporation loss with water level 3 inches below the sand surface, from material from the South Platte River taken

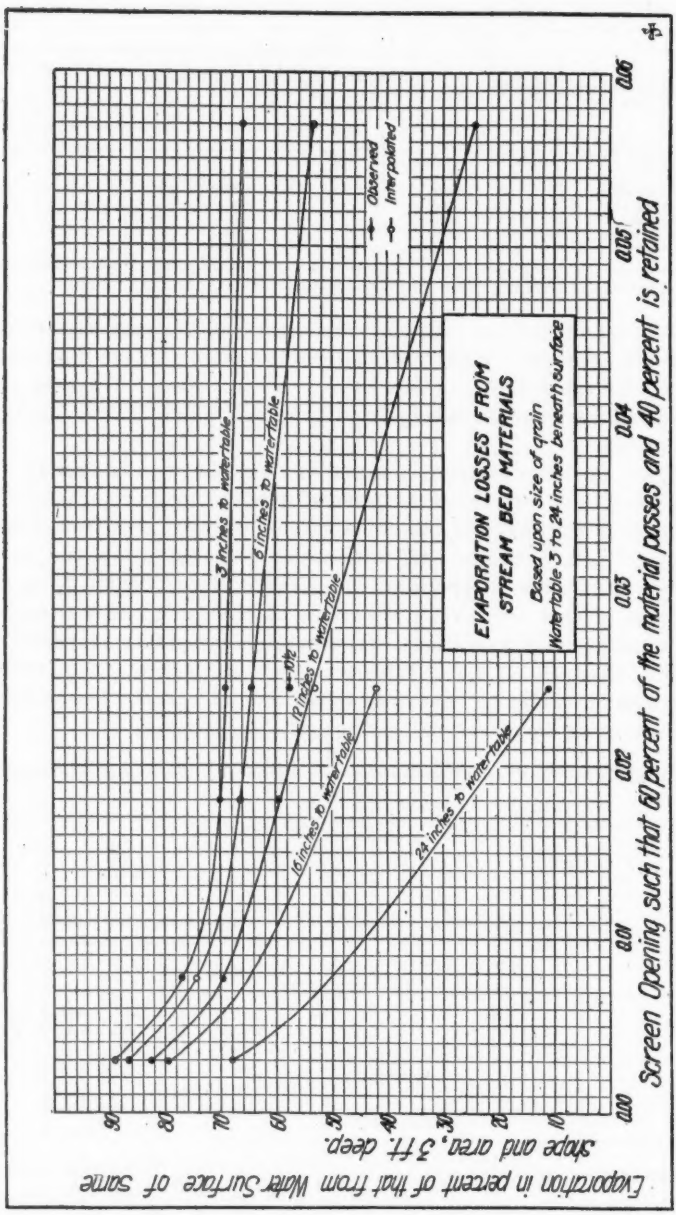

FIG. 12.—Evaporation losses from stream-bed materials.

from approximately the same point at which sample 9 was collected, was 61 per cent of that from a water surface. The 60 per cent size for that material, No. 9, as shown by figure 8, is 0.049 inch. From the upper curve of figure 12 the evaporation percentage corresponding to 0.049 inch is 67. Considering the fact that the North Platte work was done by means of tanks only 8 inches in diameter and the com-

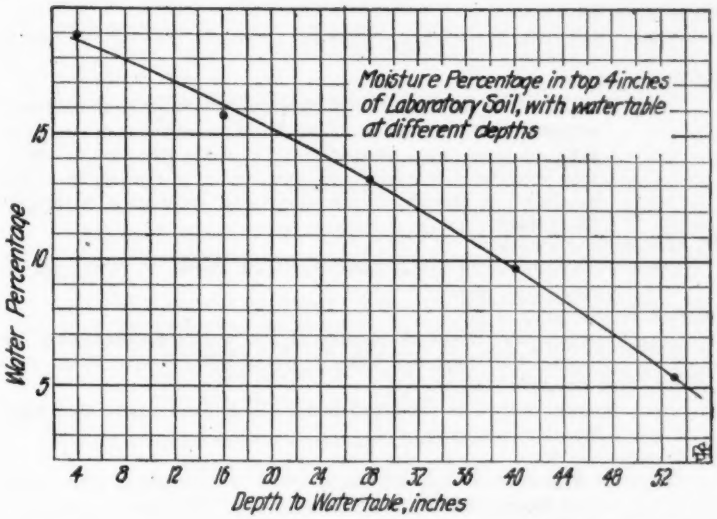

FIG. 13.—Moisture percentage in top 4 inches of Laboratory soil with water table at different depths.

parison made with a water surface tank in which the water was 2 inches deep, this check is considered close. Table XXVI will aid in the use of these data.

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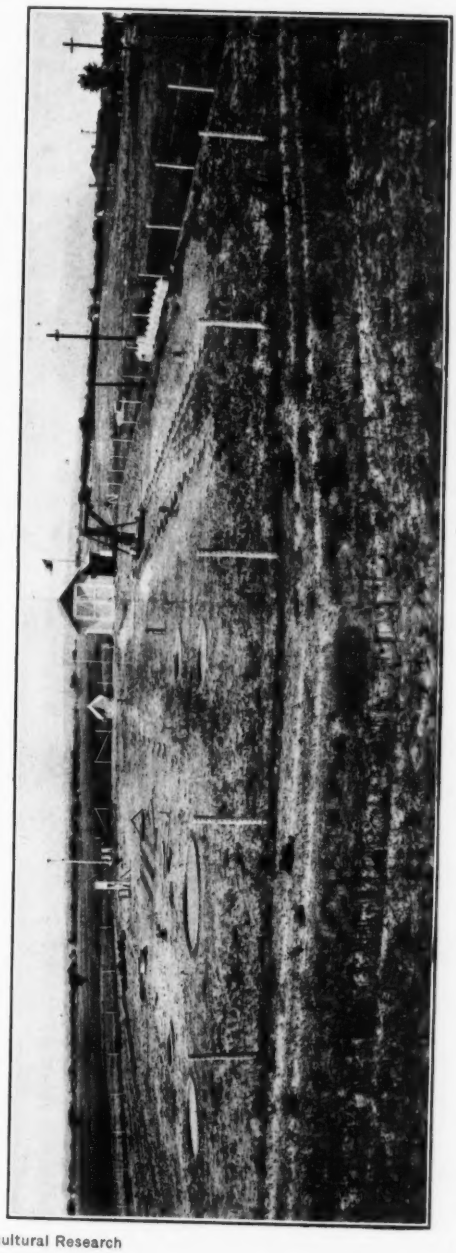
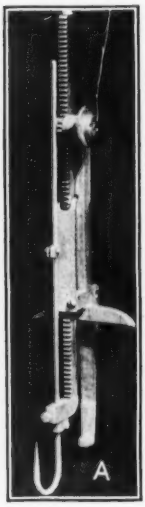
PLATE 33

General view of the irrigation field laboratory, Denver, Colo., looking west.

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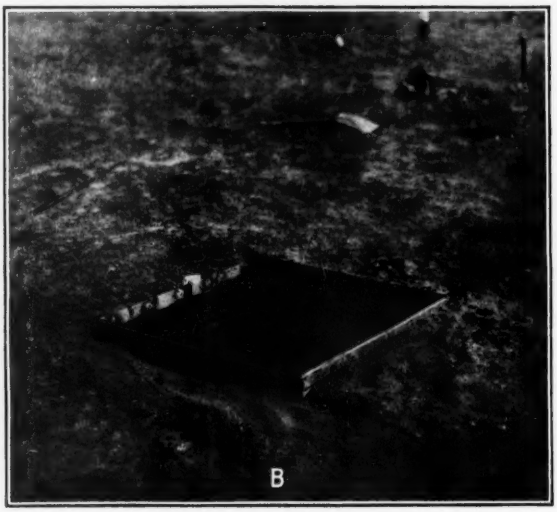
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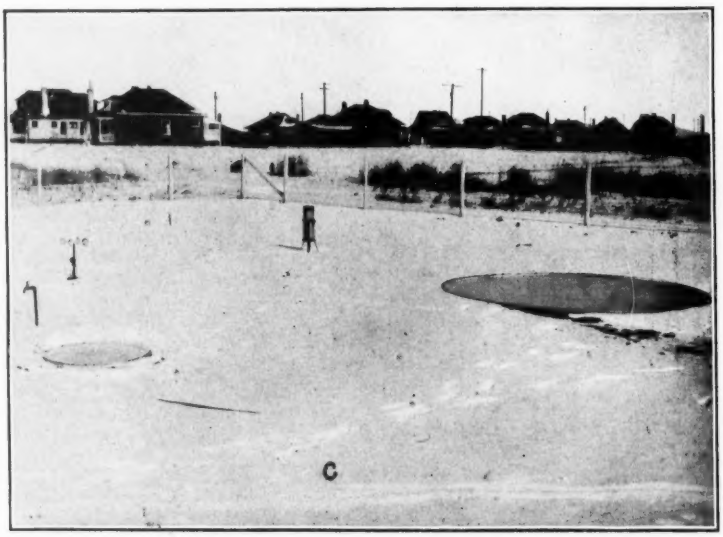
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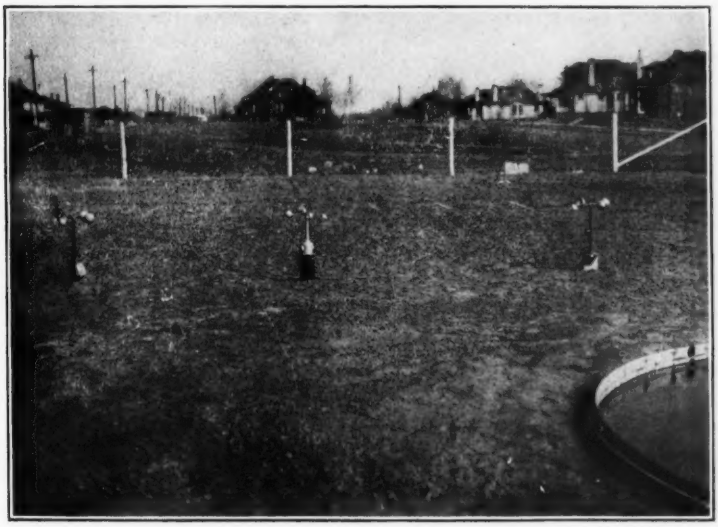
PLATE 34

A.—Hoff hook gage for evaporation.
B.—Evaporation tank 3 after a sandstorm.
C.—Snow-covered evaporation tanks 4 and 7.

PLATE 35

A.—Three anemometers during a test run.
B.—Evaporation tank 7.



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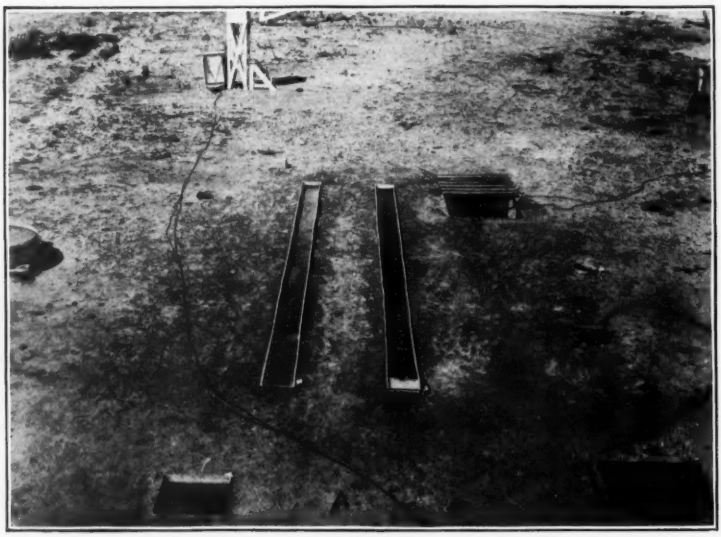
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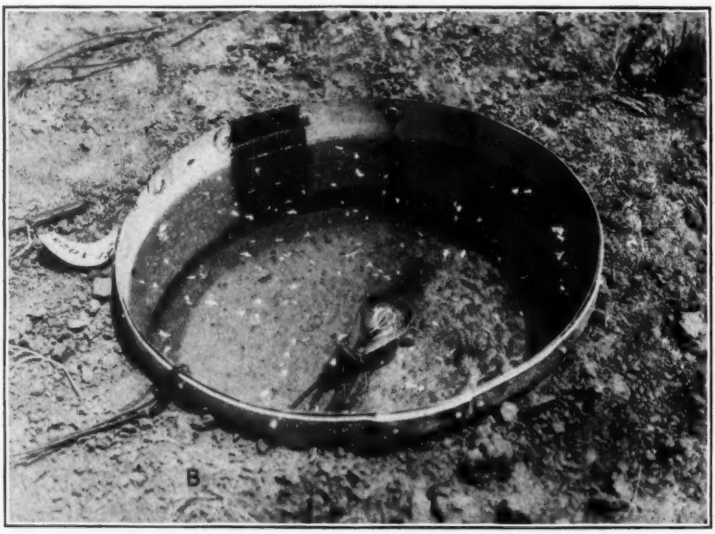
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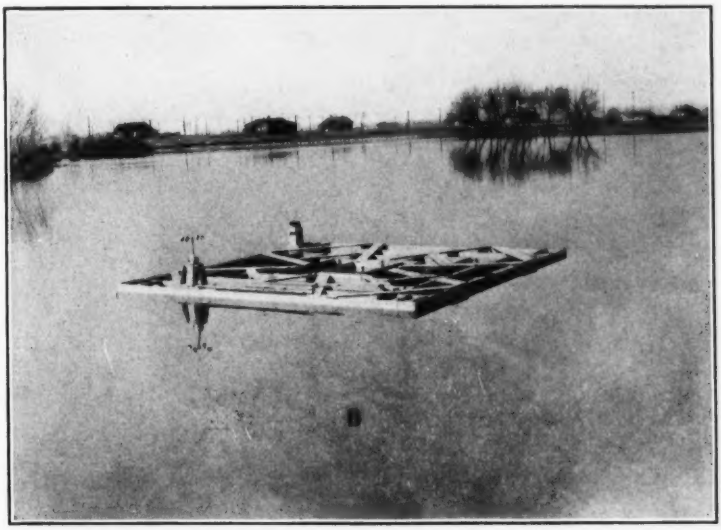
PLATE 36

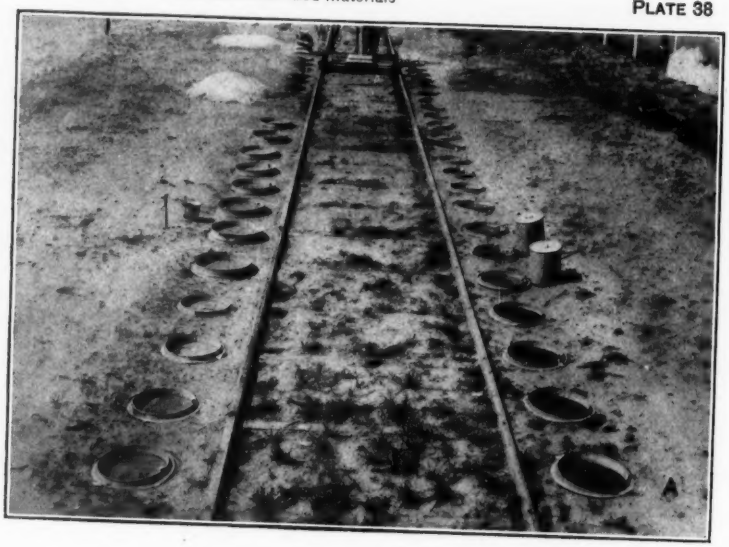
A.—Apparatus used for comparison between still and flowing water, together with tanks 8, 15, and 3.

B.—A heated evaporation tank similar to No. 23, 24, and 25.

PLATE 37

A.—United States Weather Bureau standard pan for class A station.
B.—United States Geological Survey standard floating tank.

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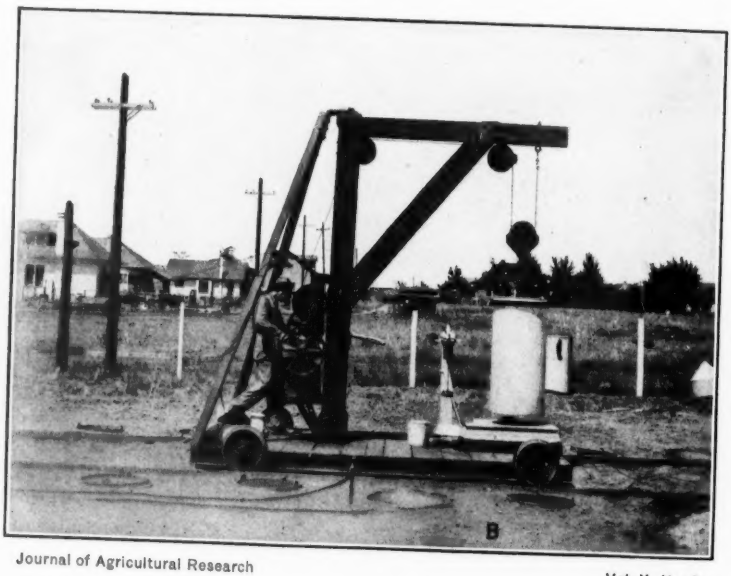
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PLATE 38

A.—Water-jacketed evaporation tanks of the Fortier type.
B.—Apparatus for weighing tanks.

INFLUENCE OF GRADING ON THE VALUE OF FINE AGGREGATE USED IN PORTLAND CEMENT CONCRETE ROAD CONSTRUCTION

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THE PROBLEM

Everyone familiar with either the testing of cement concrete or its practical use in various forms of construction realizes the marked effect variations in the grading of the aggregates may have on its strength, density, and other properties. It is known, for instance, that, other things being equal, the use of a coarse sand combined with a uniformly graded coarse aggregate will result in the production of a very much better grade of concrete than will the use of either a fine sand, a poorly graded coarse aggregate, or both. The importance of this matter, with special reference to the use of concrete as a road-surfacing material, has been much emphasized recently before engineering societies and elsewhere. The conclusions so far drawn, however, are apparently based upon the generally accepted principle as applied to the ordinary use of concrete rather than upon definite tests made with the object of determining the effect of variations in either the quality or grading of the aggregate on the resistance of concrete to the peculiar destructive forces encountered on a road. It is, of course, apparent that these forces are not only more severe but are more varied than those which act upon unreinforced concrete as ordinarily used, which is usually subjected only to direct compression.

Agencies particularly destructive to a concrete road are (1) traffic, (2) weather, and (3) constructional defects, all of which produce stresses in the concrete which should be taken care of as completely as possible through an intelligent selection of materials as well as a proper observance of the details of construction.

Traffic operates as a destructive force in three ways: (1) Iron tires cause an abrasion or grinding away of the particles composing the surface of the pavement, which varies inversely with the hardness of the concrete. (2) Suddenly applied loads, horses' hoofs, etc., subject the pavement to impact, tending to loosen and sometimes fracture the individual fragments composing the aggregate, and is resisted by the property of toughness in the material. (3) The actual weight of traffic as transmitted by wheel loads produces also compressive stresses proportional to the unit loads, but these are of much less importance in causing

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wear than are the stresses produced by abrasion and impact. The combined destructive effect of abrasion and impact therefore may be called the effect of wear, so that any concrete which will successfully resist these two forces may be said to possess high resistance to wear.

The influences of the weather tend to stress the concrete sometimes in tension and sometimes in compression, either through the action of temperature or moisture changes, or both, and usually result in the formation of cracks whose edges, unless adequately maintained, subsequently wear rapidly under the action of traffic.

Constructional defects usually result in unduly stressing the concrete at some particular point, such as might be caused by settlement due to improper consolidation of the subbase. Traffic undoubtedly is the most important destructive agency in so far as the ultimate life of the road is concerned, because its effects are cumulative and also serve to hasten deterioration started from other causes. With this point in mind, it follows that a determination of the suitability of concrete for use as a road material should be essentially a determination of its resistance to wear; and, since resistance to wear means both resistance to abrasion and impact, it would seem that hardness, and toughness tests, or a single test combining both, should be logical ones to apply.

It is the purpose of this paper to present some results obtained recently in the laboratory of the Office of Public Roads and Rural Engineering, which show in a general way the possible effect of variations in the grading of fine aggregate on each of these essential properties. Of course, it is realized that grading is only one of a number of properties of the aggregates which may influence the quality of the finished product. The character of the particles themselves, whether they are of a hard siliceous or soft calcareous nature, as well as the amount of impurities, organic or otherwise, present, is of the utmost importance. In the following tests, however, these influences were controlled by the use of a standard aggregate which was artificially graded in the laboratory prior to use.

In the case of rock used in macadam-road construction the nature of the material is such that its hardness and toughness may be determined readily, either by means of independent tests or by means of a wear test in which both properties are measured. These tests have become well known, but, because the principles involved have been used in this work, they will be discussed very briefly here. The hardness of a rock is determined by subjecting a cylindrical specimen, prepared by means of a diamond drill, to the abrasive action of crushed quartz sand of a definite size. The rock cylinder is held against a horizontally revolving steel disk upon which the abrasive is fed. The loss in weight is determined after a given number of revolutions, and this loss is used as an index of the hardness of the material.

Toughness is measured by subjecting a cylindrical rock core, 1 by 1 inch in size, to the impact produced by the fall of a given weight through successively increasing heights until failure occurs.

The combined effects of both abrasion and impact are measured together by means of the well-known Deval abrasion test, in which a standard weight of material is rattled in a cast-iron drum in such a way that the pieces composing the sample are subjected to both influences. The weight of charge larger than a certain size after a given number of revolutions measures the resistance to wear.

From a consideration of these tests it is seen at once that, with the exception of rock or slag, they are not adapted to a direct determination of the quality of concrete aggregates. The Deval test in modified form has been used to determine the resistance to wear of gravel and sand, but its use for this purpose, though promising, still is in the experimental stage. It is manifestly impossible to test the wearing qualities of fine aggregates directly by any of these methods. Either the hardness or toughness test or a wear test may, however, be applied to the fine aggregate when combined with cement to form a mortar or with cement and coarse aggregate to form concrete. Wear tests of mortar and concrete have been made with the Deval machine, the Tablot-Jones brick rattler, and other special devices. Of these the adaptation of the brick rattler as described by Abrams [1] appears to be the nearest solution of the problem of obtaining a laboratory wear test. Only preliminary results of tests using this method have been published. Wear tests of concrete in place on the road have been confined largely to suggestions for suitable methods, although tests using the apparatus designed by Goldbeck [2] have been started on an experimental concrete road near Washington, D. C.

EXPERIMENTAL WORK

In the following tests the effect of varying the grading of sand on the hardness, toughness, tensile strength, and crushing strength of mortars has been studied. The fine aggregate was prepared by artificially grading a quantity of Potomac River concrete sand, the analysis of which is shown in Table I into three sizes as follows:

(1) A coarse sand (*C*) composed of equal parts of material passing a ¼-inch screen but retained on a 10-mesh sieve and that passing a 10-mesh but retained on a 20-mesh sieve.

(2) A medium sand (*M*) composed of equal parts of 20 to 30 mesh, 30 to 40 mesh, and 40 to 50 mesh material.

(3) A fine sand (*F*) composed of the run of the sand below No. 50.

[1] ABRAMS, D. A. A METHOD OF MAKING WEAR TESTS OF CONCRETE. *In* Amer. Soc. Testing Materials Proc. 19th Ann. Meeting, 1916, v. 16, pt. 2, p. 194–202. 1916.

[2] GOLDBECK, A. T. APPARATUS FOR MEASURING THE WEAR OF CONCRETE ROADS. *In* Jour. Agr. Research, v. 5, no. 20, p. 951–954, pl. 66. 1916.

TABLE I.—*Mechanical analysis of natural sand*

Mesh of sieve.	Percentage passing.	Mesh of sieve.	Percentage passing.
Between ¼ inch and No. 10	15.9	Between No. 80 and 100	2.4
Between No. 10 and 20	21.8	Between No. 100 and 200	3.3
Between No. 20 and 30	21.2	Under 200	2.8
Between No. 30 and 40	13.3		
Between No. 40 and 50	7.9	Total	100.0
Between No. 50 and 80	11.4		

The fine sand contained about 10 per cent that passed a 200-mesh sieve.

The sands graded as above then were recombined into 60 different combinations of coarse, medium, and fine, as shown in Table II, in which the equivalent mechanical analysis of each combination is also shown. The resulting sands were made up into standard mortar briquettes and 2 by 2 inch cylinders, using a mixture composed of 1 part of cement to 2½ parts of sand. All the batches were brought to as nearly the same consistency as it was possible to judge by the eye, which necessitated the use of varying percentages of water. Specimens were stored in moist air one day and in water six days and then were tested to determine their hardness, toughness, tensile strength, and crushing strength.

TABLE II.—*Proportion of artificially graded sands*

Laboratory No.	Proportions.			Equivalent mechanical analysis—per cent between—					
	C.	M.	F.	¼-inch and No. 10.	10 and 20.	20 and 30.	30 and 40.	40 and 50.	Under No. 50.
	Per ct.	*Per ct.*	*Per ct.*						
1	100	0	0	50	50	0	0	0	0
2	80	0	20	40	40	0	0	0	20
3	80	10	10	40	40	3.3	3.3	3.3	10
4	80	20	0	40	40	6.6	6.6	6.6	0
5	70	0	30	35	35	0	0	0	30
6	70	10	20	35	35	3.3	3.3	3.3	20
7	70	20	10	35	35	6.6	6.6	6.6	10
8	60	0	40	30	30	0	0	0	40
9	60	10	30	30	30	3.3	3.3	3.3	30
10	60	20	20	30	30	6.6	6.6	6.6	20
11	60	30	10	30	30	10	10	10	10
12	60	40	0	30	30	13.3	13.3	13.3	0
13	50	0	50	25	25	0	0	0	50
14	50	10	40	25	25	3.3	3.3	3.3	40
15	50	20	30	25	25	6.6	6.6	6.6	30
16	50	30	20	25	25	10	10	10	20
17	50	40	10	25	25	13.3	13.3	13.3	10
18	40	0	60	20	20	0	0	0	60
19	40	10	50	20	20	3.3	3.3	3.3	50
20	40	20	40	20	20	6.6	6.6	6.6	40
21	40	30	30	20	20	10	10	10	30
22	40	40	20	20	20	13.3	13.3	13.3	20
23	40	50	10	20	20	16.6	16.6	16.6	10

TABLE II.—*Proportion of artificially graded sands*—Continued

Laboratory No.	Proportions.			Equivalent mechanical analysis—per cent between—					
	C.	M.	F.	¼-inch and No. 10.	10 and 20.	20 and 30.	30 and 40.	40 and 50.	Under No. 50.
	Per ct.	*Per ct.*	*Per ct.*						
24	40	60	0	20	20	20	20	20	0
25	30	0	70	15	15	0	0	0	70
26	30	10	60	15	15	3.3	3.3	3.3	60
27	30	20	50	15	15	6.6	6.6	6.6	50
28	30	30	40	15	15	10	10	10	40
29	30	40	30	15	15	13.3	13.3	13.3	30
30	30	50	20	15	15	16.6	16.6	16.6	20
31	30	60	10	15	15	20	20	20	10
32	20	0	80	10	10	0	0	0	80
33	20	10	70	10	10	3.3	3.3	3.3	70
34	20	20	60	10	10	6.6	6.6	6.6	60
35	20	30	50	10	10	10	10	10	50
36	20	40	40	10	10	13.3	13.3	13.3	40
37	20	50	30	10	10	16.6	16.6	16.6	30
38	20	60	20	10	10	20	20	20	20
39	20	70	10	10	10	23.3	23.3	23.3	10
40	20	80	0	10	10	26.6	26.6	26.6	0
41	10	0	90	5	5	0	0	0	90
42	10	10	80	5	5	3.3	3.3	3.3	80
43	10	20	70	5	5	6.6	6.6	6.6	70
44	10	30	60	5	5	10	10	10	60
45	10	40	50	5	5	13.3	13.3	13.3	50
46	10	50	40	5	5	16.6	16.6	16.6	40
47	10	60	30	5	5	20	20	20	30
48	10	70	20	5	5	23.3	23.3	23.3	20
49	10	80	10	5	5	26.6	26.6	26.6	10
50	0	0	100	0	0	0	0	0	100
51	0	10	90	0	0	3.3	3.3	3.3	90
52	0	20	80	0	0	6.6	6.6	6.6	80
53	0	30	70	0	0	10	10	10	70
54	0	40	60	0	0	13.3	13.3	13.3	60
55	0	50	50	0	0	16.6	16.6	16.6	50
56	0	60	40	0	0	20	20	20	40
57	0	70	30	0	0	23.3	23.3	23.3	30
58	0	80	20	0	0	26.6	26.6	26.6	20
59	0	90	10	0	0	30	30	30	10
60	0	100	0	0	0	33.3	33.3	33.3	0

HARDNESS TESTS

Specimens for the hardness tests were prepared by drilling 1-inch cores through the center of the 2-inch cylinders and drying them thoroughly in a hot-air oven. They were tested then for hardness in the same manner as the hardness of rock is obtained, as described above, by holding the ends of the specimens against a revolving steel disk upon which quartz sand was fed as the abrasive. The specimens were weighed carefully before and after 1,000 revolutions of the disk, and the loss in weight was used as an index of the hardness of the mortar. The results of the hardness tests on all the sand mixtures studied are shown

in figure 1, in which the loss in weight of the various specimens is plotted on a Feret triangle at the points indicating the proportions of coarse, medium, and fine sand in the mix. Several interesting facts are shown in this figure. First, it is seen that the loss in weight of all specimens is practically constant for all mixtures containing more than 10 per cent of the coarse sand. This loss, averaging about 5 gm., is very slightly more than would be obtained on a specimen of solid quartz tested in the same way. In other words, the hardness of all specimens containing an appreciable amount of sand over 20 mesh in size appears to be a function of the hardness of the aggregate itself independent of the grading. On referring to the specimens containing various percentages of medium and fine sand, but no coarse, it will be noted that the loss in weight is very much greater, amounting in two cases to more than 250 gm. By assuming that the actual hardness of the coarse and medium sand grains is the same, in view of the fact that the sand was composed of practically pure quartz, these results show that the use of the fine sand has so weakened the adhesion between the cement and the individual particles of aggregate by enormously increasing its superficial area that the specimens disintegrated readily under the action of the abrasive.

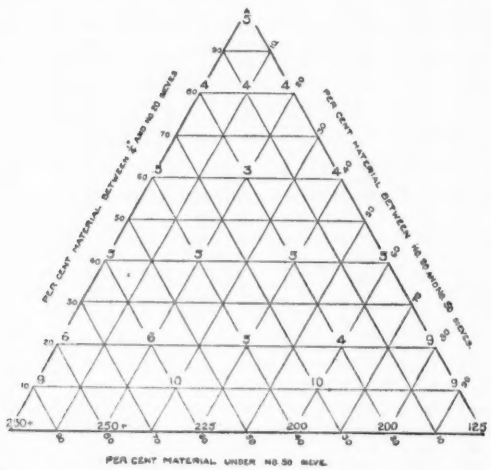

FIG. 1.—Graph of hardness tests of artificially graded sand mortar. Proportions 1 to 2½ by weight.

In order to determine the hardness of mortar containing very fine sand in a rich mix, as compared to the 1-to-2½ mixes, a few tests were made using sands artificially graded as above in the proportion of 1 part of cement to 1½ parts of sand. In the case of mixtures containing coarse sand, losses practically identical with those shown on figure 1 were found. In the case of the very fine sands, however, an average loss of about 40 instead of 200 was noted. This would indicate that the hardness of a mortar containing a large amount of extremely fine sand may be increased considerably by increasing the quantity of cement. Even in this case, however, the average loss is greatly in excess of that obtained by the use of a coarse sand.

In figure 2 the results of the 1-to-2½ mortar tests are shown plotted on rectangular coordinates with the percentage of sand over 20 mesh as abscissæ and the loss in weight per 1,000 revolutions as ordinates. Each point plotted represents the average of the results on all values obtained originally with the percentage of coarse sand as indicated. For instance, the average of all combinations of medium and fine sand with 20 per cent coarse showed a loss of 6 gm., and this value is plotted on the curve. This graph shows the great effect of coarse sand on the hardness of mortar. The corresponding curve (not shown) for the hardness of 1-to-1½ mortars was found to be practically identical, except that the average loss for mortars containing no percentage of sand over 20 mesh was 40 instead of 200.

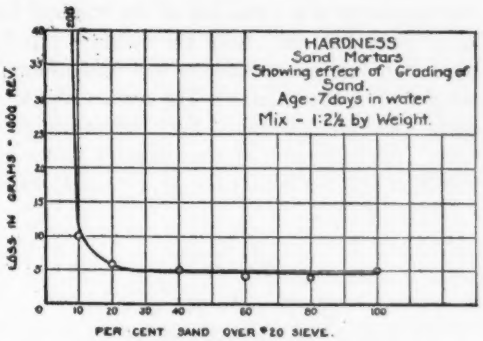
HARDNESS
Sand Mortars
Showing effect of Grading of Sand.
Age - 7days in water
Mix - 1:2½ by Weight.
LOSS IN GRAMS - 1000 REV.
PER CENT SAND OVER #20 SIEVE.

FIG. 2.—Curve of hardness tests of artificially graded sand mortar.

Figure 3 shows the results of a number of hardness tests made on a series of mortar specimens, in which the grading of the sand remained constant and the percentage of cement varied. In these tests the unscreened Potomac River sand, similar in quality to the artificially graded sands, was used. It will be seen that the hardness values of the mortar specimens are all greater than neat cement. Furthermore, there is very little difference in the loss in weight between the 1-to-1, 1-to-1½, 1-to-2, and 1-to-3 mixes, all of which show about the same hardness as was obtained with the artificially graded coarse sands. The somewhat greater loss sustained by the 1-to-4 mortar specimen, no doubt, is due to the very lean mix, which allowed the mortar to disintegrate under the test in much the same way as noted above for very fine sand.

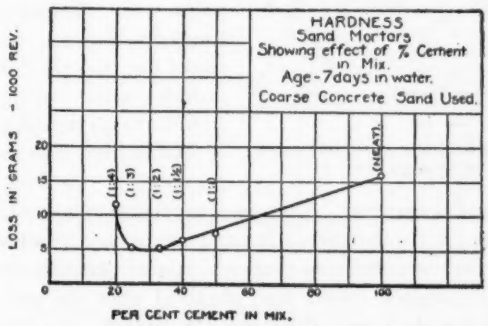
HARDNESS
Sand Mortars
Showing effect of % Cement in Mix.
Age - 7days in water.
Coarse Concrete Sand Used.
LOSS IN GRAMS - 1000 REV.
PER CENT CEMENT IN MIX.

FIG. 3.—Curve of hardness tests of natural concrete sand mortars.

TOUGHNESS TESTS

Toughness tests were made on 2- by 2-inch cylinders, using the Page impact machine for testing rock. The procedure was similar to that employed in the standard rock test, except that a 2-inch instead of a 1-inch cylinder and a ½ instead of a 2 kgm. hammer were used. The test consisted of a 1-cm. fall of the hammer for the first blow, followed by a 2-cm. fall, etc., until the cylinder was fractured. The height of blow at failure in centimeters was used as an indication of the relative toughness of the mortar. The results of tests are plotted in figure 4, using the Feret triangle. Each result plotted is the average of three tests. An inspection of the diagram shows at once that considerable variation in toughness may be obtained, owing to differences in sand grading, but that, in general, toughness increases with the percentage of coarse sand in the mix. The contour lines, which bound areas of equal toughness, show in a general way the relative resistance to impact developed by the use of different mixtures. The area of maximum toughness is seen at the top of the triangle and includes sand having from 60 to 90 per cent of coarse, from 0 to 20 per cent of medium, and from 5 to 35 per cent of fine material. The area of minimum toughness, as would be expected, lies toward the lower left-hand corner and includes the very fine sands. It may be noted also that, with a given percentage of coarse sand, say 50, the highest results were obtained when the proportions of medium and fine sand were about equally divided. On the other hand, for a given percentage of either medium or fine sand, the toughness appears to increase as the proportion of coarse sand increases. In general, it would seem that the toughness of a cement mortar increases with the amount of coarse sand present in the aggregate up to the limit of maximum toughness, which, for this mix appears to be obtained with a sand having about 80 per cent of coarse, 10 per cent of medium, and 10 per cent of fine material. The general effect of coarse sand on toughness is shown clearly in figure 5, which is replotted from the results shown

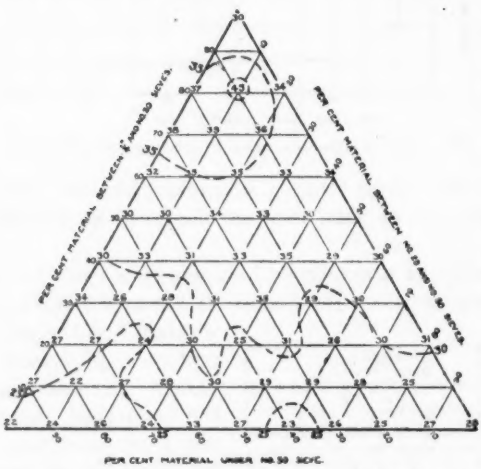

FIG. 4.—Graph of toughness tests of artificially graded sand mortar. Proportions 1 to 2½ by weight.

in figure 4 in the same way as the results of the hardness tests previously referred to.

A series of tests made with the view of determining the effect of richness of mix on the toughness of cement mortar are shown, for comparison, in figure 6. The results are plotted with the percentage of cement as abscissæ and toughness as ordinates. Each plotted result is the average of nine tests. These results are of interest in showing the large increase in toughness produced by increasing the cement content. This increase appears to be practically proportional to the percentage of cement up to a 1-to-1 mix, after which the addition of more cement affects the toughness very little. In other words, a neat cement briquette is no tougher than one composed of equal parts of cement and a typical concrete sand, which, in turn, shows twice the resistance to impact of one containing only 20 per cent. Inasmuch as this sand was very well graded and contained only 35 per cent of voids, it is obvious that a considerable excess of cement over that required to fill the voids is required to reach the condition of maximum toughness. In other words, these results present an experimental verification of the theory which requires the use of a rich mix in the surface of a concrete pavement, especially as has been seen by reference to the hardness test shown in figure 3 that the hardness of a rich 1-to-1½ mix is practically the same as a 1-to-3 and greater than a 1-to-4 mix.

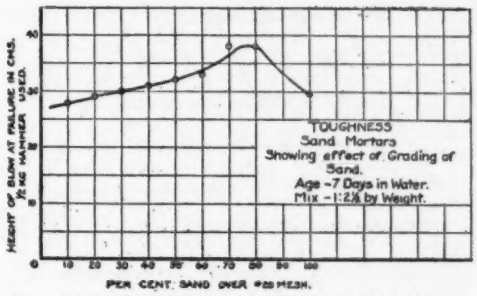
TOUGHNESS
Sand Mortars
Showing effect of Grading of Sand.
Age – 7 Days in Water.
Mix – 1:2½ by Weight.
HEIGHT OF BLOW AT FAILURE IN CMS. 2 KG HAMMER USED.
PER CENT. SAND OVER #20 MESH.

FIG. 5.—Curve of toughness tests of artificially graded sand mortar.

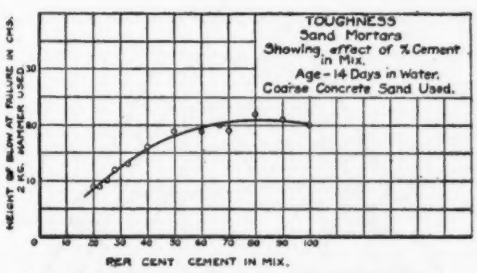
TOUGHNESS
Sand Mortars
Showing effect of % Cement in Mix.
Age – 14 Days in Water.
Coarse Concrete Sand Used.
HEIGHT OF BLOW AT FAILURE IN CMS. 2 KG. HAMMER USED.
PER CENT CEMENT IN MIX.

FIG. 6.—Curve of toughness tests of natural concrete sand mortar.

TENSION AND COMPRESSION TESTS

The results of the tension and compression tests are shown in figures 7 and 8. They were made in the usual way on standard briquettes and 2 by 2 inch cylinders. Each value in tension is the average of six tests,

and each value in compression the average of three tests. The average total variation in individual results of each set was 10 per cent for tension and 5 per cent for compression. The results show graphically the enormous variation which may be obtained in both the tensile and compressive strength of mortar by reason of variations in the grading of the sand. The contour lines are much more regular than those showing variations in toughness. The following points may be noted:

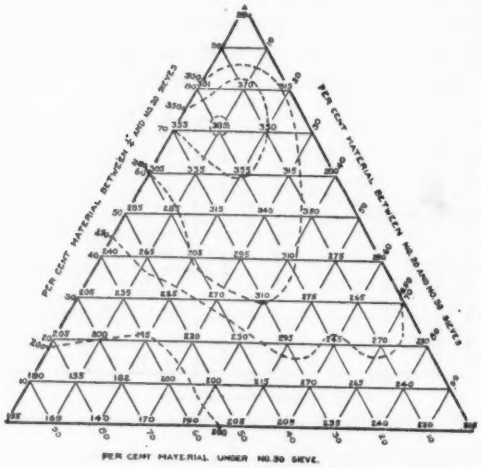
PER CENT MATERIAL BETWEEN ¼" AND NO.10 SIEVE.
PER CENT MATERIAL BETWEEN NO.10 AND NO.30 SIEVES.
PER CENT MATERIAL UNDER NO.30 SIEVE.

FIG. 7.—Graph of tension tests of artificially graded sand mortars. Proportions 1 to 2½ by weight.

TENSION.—Sands showing maximum results in tension are composed of from 60 to 80 per cent coarse, 0 to 20 per cent medium, and 10 to 30 per cent fine, whereas the weakest sands are those composed of from 0 to 10 per cent coarse, 0 to 20 per cent medium, and 80 to 100 per cent fine. A sand composed of 100 per cent coarse is 35 per cent stronger than one composed of medium only and 80 per cent stronger than one composed of fine only, but is nearly 40 per cent weaker than the sand of maximum strength (70–10–20). The total variation in strength is 250 pounds per square inch, or 54 per cent from the average of the 60 determinations.

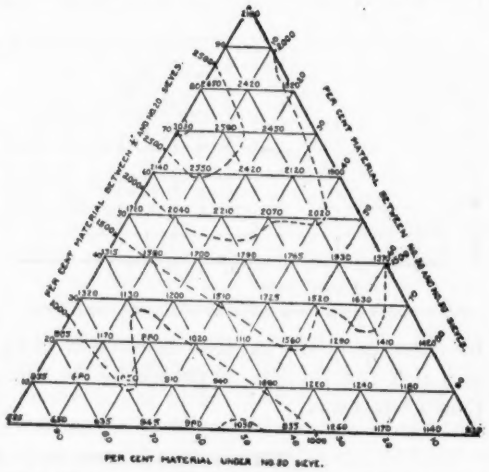
PER CENT MATERIAL BETWEEN ¼" AND NO.10 SIEVES.
PER CENT MATERIAL BETWEEN NO.10 AND NO.30 SIEVES.
PER CENT MATERIAL UNDER NO.30 SIEVE.

FIG. 8.—Graph of compression tests of artificially graded sand mortars. Proportions 1 to 2½ by weight.

COMPRESSION.—Sands showing maximum results in compression are composed of from 60 to 80 per cent coarse, 0 to 20 per cent medium and 10 to 30 per cent fine, the same limits as for tension. A sand composed

of 100 per cent coarse is 95 per cent stronger than one composed of fine only, but is 35 per cent weaker than the strongest sand (70–0–30). The total variation in strength is 2,505 pounds per square inch, or 100 per cent from the average of 60 determinations.

In figures 9 and 10 the results of the tension and compression tests are replotted on rectangular coordinates to show the effect of the coarse sand (¼ inch to No. 20 mesh) on the strength of the mortar. The most interesting feature about these curves, apart from their regularity, is the very great variation in strength shown, especially in compression. Thus, without considering either the very coarse or very fine sand, which would be used rarely in actual construction, the variations in strength are still large. Let it be assumed, for instance, that a specification calls for a sand which shall show from 20 to 50 per cent retained on the No. 20 sieve. The results of these tests show a possible variation in compression of from 1,200 to 2,000 pounds per square inch for sands fulfilling this requirement. They show also that much higher strength may be obtained in the mortar by the use of coarser sands up to as high as 70 per cent retained on a 20-mesh sieve.

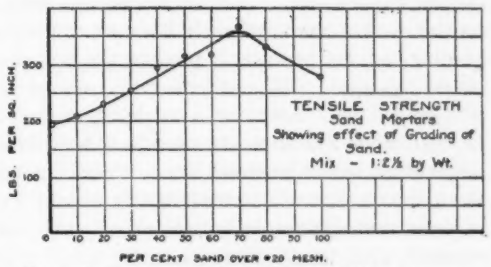

FIG. 9.—Curve of tension tests of artificially graded sand mortars.

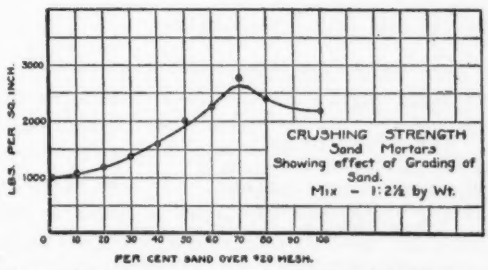

FIG. 10.—Curve of compression tests of artificially graded sand mortars.

It is realized, of course, that such coarse sands seldom are met with in practice and, if they were, would not be used in ordinary work where a considerable amount of fine material is needed to produce workability. It must be borne in mind, however, that concrete-pavement construction is not ordinary work on account of the severity and variety of the destructive forces encountered. It has been the custom to meet this condition by increasing the amount of cement to about 40 per cent of the mortar in a 1-to-5 mix, and, while this is good practice, it seems reasonable to suppose that a still greater resistance to these destructive agencies would be obtained by increasing the amount of the coarse sand which takes this wear (the ¼ inch to 20-mesh material) over that which is usually considered good

practice. This would seem to be allowable, especially in view of the large excess of cement that is always used. When one considers that a large proportion of the wearing surface of a concrete pavement is composed of mortar, the danger of using a fine sand, with subsequent weakening of the matrix, is apparent.

In the foregoing discussion it is realized that but few naturally occurring concrete sands are as coarse as those making the strongest mortars, according to these tests. Neither has the fact been overlooked that the best mortar, when combined with stone or gravel, without reference to its grading, will not necessarily produce the best concrete. A poorly graded coarse aggregate will unquestionably require more mortar than will a well-graded one. Likewise, a coarse aggregate containing a large amount of small stone will allow the use of a somewhat finer sand than when the larger-sized stones predominate. When it is considered, however, that the mortar in concrete forms a matrix by which the larger stones are held in place, that this matrix occupies nearly one-half the total volume of the concrete, and, finally, that its strength and toughness are undoubtedly influenced to a large degree by the grading of the sand, the discussion becomes of practical value. So important does it become that it might even be considered practical to use a graded rather than a naturally occurring concrete sand in such important work as concrete-road construction if by so doing the life of the pavement can be prolonged.

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